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Profile of the Chemicals Industry in California

California Industries of the Future Program

Christina Galitsky and Ernst Worrell

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Energy Analysis Department
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 94720

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Executive Summary

The U.S. Department of Energy (DOE) Office of Industrial Technologies (OIT) established the Industries of the Future (IOF) program to increase energy efficiency, reduce waste production and to improve competitiveness, currently focusing on nine sectors. The IOF is a partnership strategy involving industry, the research community and the government, working together to identify technology needs, promote industrial partnerships and implement joint measures with all partners involved.

The State Industries of the Future (SIOF) program delivers the accomplishments of the national Industries of the Future strategy to the local level, to expand the technology opportunities to a larger number of partners and reach smaller businesses and manufacturers that were not initially involved in the IOF effort. The state programs bring together industry, academia, and state agencies to address the important issues confronting industry in the state. These public-private coalitions facilitate industry solutions locally and enhance economic development. California has started a State Industries of the Future effort in collaboration with the U.S. Department of Energy.

The California Energy Commission (CEC) is leading the SIOF program in California, as part of many other programs to improve the energy efficiency and performance of industries in California. The California State IOF program aims to build a network of participants from industry, academia and government in four selected industrial sectors as a basis for the development of a strategic partnership for industrial energy efficient technology in the state. In California the IOF effort focuses on petroleum refining, chemical processing, food processing and electronics. As part of this effort, the SIOF program will develop roadmaps for technology development for the selected sectors. On the basis of the roadmap, the program will develop successful projects with co-funding from state and federal government, and promote industry-specific energy-efficiency. This report aims to provide background information for the development of a research and development roadmap for the Californian chemical manufacturing industry.

The chemical industry is an important part of the Californian economy. The Californian chemical industry includes a very wide mix of products, with the dominant sub-sectors being pharmaceuticals, inorganic chemicals, organic chemicals, plastics and resins and soap and detergents. The structure of the Californian chemical industry varies widely from that of the United States. In California the focus in on industries with a relatively low energy-intensity (with a few exceptions) producing high value-added chemicals from intermediate feedstocks produced elsewhere. This sets the Californian chemical industry apart from the nations industry, warranting special attention in an Industries of the Future program. We estimate the primary energy consumption of the chemical industry in California at 48 TBtu in 2000 (51 PJ), excluding hydrocarbon feedstocks from petroleum products.

Due to the large differences between the Californian and U.S. chemical industries the areas for energy-efficiency improvement also vary. While much work on R&D roadmaps has been done for the national IOF program, distinct areas of interest to the specific conditions in California remain Table ES-1 summarizes the major areas for energy R&D in the chemicals industry in California.

Table ES-1. Major technology development directions for the chemical industry in California.

Technology Area	**Technology Examples**
Process Control	Neural networks, knowledge based systems, improved sensors
Process Optimization and Integration	Analytical tools, site integration, batch process integration
Energy Recovery	Hydrogen recovery and integration (with petroleum refining)
Catalysts	Higher selectivity, increased lifetime, bio-catalysts
Reactor Design	Process intensification, reactive distillation
Biotechnology	Improved controllability, selectivity and efficiency
Separations	Membranes, crystallization
Combustion Technology	Low NOx burners, high-efficiency burners
Clean rooms	New integrated and efficient designs
Utilities	Membranes, low-maintenance pumps
Power Generation	Advanced cogeneration

Contents

1. Introduction

The U.S. Department of Energy (DOE) Office of Industrial Technologies (OIT) established the Industries of the Future (IOF) program to increase energy efficiency, reduce waste production and to improve competitiveness, currently focusing on nine sectors. The IOF is a partnership strategy involving industry, the research community and the government, working together to identify technology needs, promote industrial partnerships and implement joint measures with all partners involved.

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An important element of the SIOF-program is the preparation of R&D roadmaps for each of the selected industries. The roadmap will help to identify priority needs for the participating industries to meet their energy challenges. The roadmap effort builds on the roadmaps developed by DOE, and on the conditions specific for the industry in California. Key to the successful preparation of a roadmap in the selected industries is the development of a profile of the industries. The profile provides a basis for the participants in the roadmap-effort, especially as the structure of the industries in California can be different than in the nation. The sector profiles describe the current economic and energy situation of these industries in California, the processes and energy uses, and the potential future developments in each industry. The profiles are an integral part of the roadmap, to help working group partners to evaluate the industry’s R&D needs for their industry in California.

In this report, we focus on the chemicals industry. The industry is an important economic factor in the state, providing over 82,300 jobs directly, and more in indirect employment. Value of shipments in 2001 was just under $25.7 Billion, or 6% of all manufacturing in California. There are over 1,500 chemical plants in California, of which 52% are pharmaceutical companies. Many companies operate chemical plants in California. The industry consumes 8% of the electricity and 5% of the natural gas in California.

In this report, we start with a description of the chemical industry in the United States and California. This is followed by a discussion of the energy consumption and energy intensity of the Californian chemical industry. Chapter 3 focuses on the main sub-sectors. For each of the sub-sectors a general process description is provided in Chapter 4. Based on this analysis, in Chapter 5, we discuss potential technology developments that can contribute to further improving the energy efficiency in chemical plants, with a focus on the situation in California.

2. The Chemical Manufacturing Industry

We start with a description of the U.S. chemical manufacturing industry, followed by a description of the industry in California. This will help to put the Californian developments in a broader perspective, and to distinguish the developments specific for California.

2.1 The U.S. Chemical Manufacturing Industry

The U.S. is the largest chemical producer in the world, generating over a quarter of all chemicals in the world, a $1.5 trillion market. The industry provides over 2% of the total U.S. GDP and almost 12% of the GDP in the manufacturing sector. On a value-added basis, it is the largest U.S. manufacturing sector (12% of total manufacturing in 2001).

Over 70,000 products are manufactured by the chemical industry in the U.S. In addition to final products made by the chemical industry such as soaps, cleaners, bleach, cosmetics, dyes, pharmaceuticals, plastics, and other chemical products are used as intermediates in the manufacturing of rubber and plastic products, textiles, apparel, petroleum, paper and allied products and primary metals. Few goods are produced without some input from the chemical industry.

Overall, the U.S. Chemicals industry grew about 44% from 1992 to 2001, with the biggest growth from 1996 to 1997 (13%). Each year saw at least a slight increase until 2001, when the stock market crashed in the early part of the 21st century. Figure 1 shows the value of shipments for the U.S. Chemicals industry from 1992 to 2001.

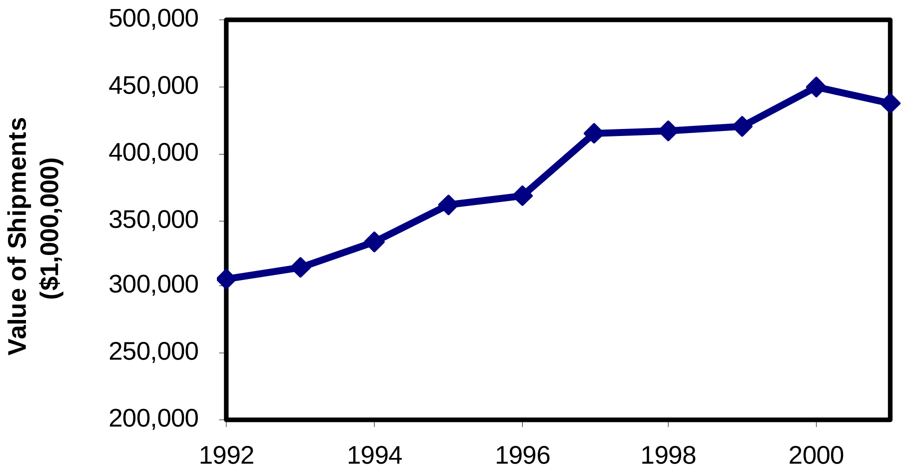

Figure 1. Value of Shipments of the U.S. Chemicals Industry from 1992 to 2001. Source: U.S. Census, Annual Survey of Manufacturers, various years.

Figure 2 shows the distribution of value of shipments throughout the U.S. Texas is the largest producer of chemicals measured in terms of value of shipments, shipping over $67 billion in 1997, 16% of the total shipments in the U.S. California is ranked eighth after

Texas, New Jersey, Louisiana, North Carolina, Illinois, Ohio and New York. California produces less than 5% of the total value of shipments in the U.S.

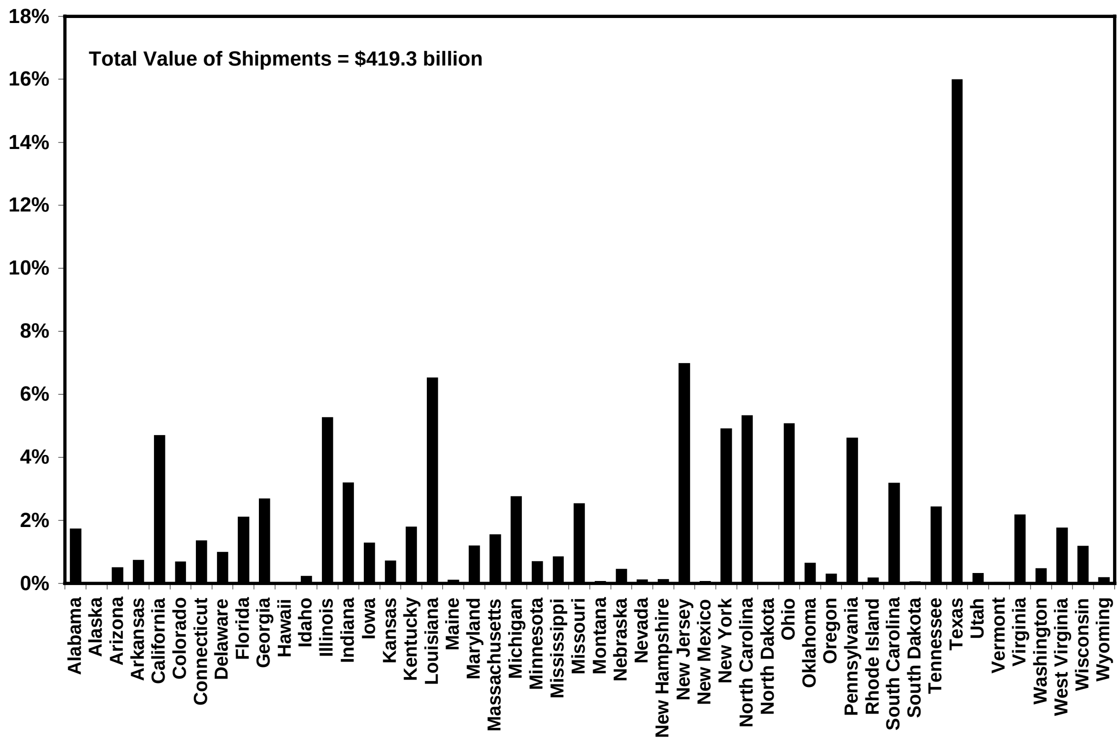

Figure 2. Distribution of the Value of Shipments in the U.S. Chemicals Industry in 1997. Source: U.S. Census, Annual Survey of Manufacturers, 1997

Pharmaceuticals, organic chemicals, plastics and synthetics, inorganic chemicals and agricultural chemicals make up 77% of shipments of chemicals in the U.S. and 93% of the energy purchases. Figure 3 shows the distribution of value of shipments for the eight sub-sectors of the chemicals industry in the U.S., categorized by three-digit SIC code.

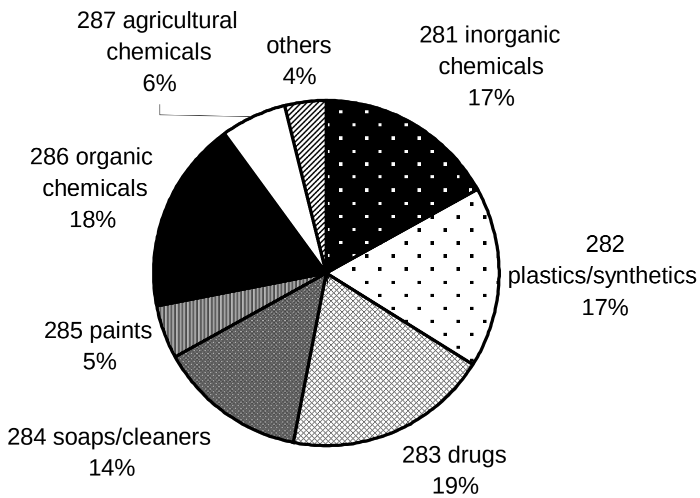

Figure 3. Value of Shipments in the U.S. Chemical Industry in 1997 by SIC code. Source: U.S. Census, Annual Survey of Manufacturers, 1997

In 1997, there were about 13,500 chemical plants across the U.S. Figure 4 shows the distribution of chemical companies throughout the U.S. Because much of the products of the chemical industry are used as intermediates to manufacture other products, chemical plants are generally concentrated in areas with other manufacturing businesses, such as the Great Lakes region (near the automotive industry) and the West Coast (near the electronics industry). Most of the basic chemical production (inorganic and organic chemicals) is concentrated along the Gulf Coast where petroleum and natural gas feedstocks are available. New Jersey, California and New York account for one third of the pharmaceutical plants, although other states like Massachusetts, North Carolina and Maryland are experiencing more growth recently. The fertilizer industry is greatly influenced by easy access to natural resources and nearby demand centers. For example, Florida has the largest phosphate rock supply in the U.S. and phosphoric acid is mainly manufactured in Florida and the nearby Southeastern states. The majority of nitric acid plants are located in agricultural demand centers like the Midwest, South Central and Gulf states. About one quarter of the fertilizers produced in the U.S. are manufactured in Florida, Texas, Ohio, California, North Carolina and Louisiana. The inorganic chemical industry is more fragmented. They are generally located near consumers and, to a lesser extent, raw materials. The largest use of inorganic chemicals is in other industrial processes. Hence, most of the facilities are located in the industrial regions of the Gulf Coast, the east and west coasts and the Great Lakes region. Many inorganic chemicals are used by the organic chemical manufacturing industry. Therefore, the geographical distribution of the organic chemical industry is similar to the inorganic industry. Gum and wood chemical production is found primarily in the southeast near wood and pulp production facilities. Other organic chemical facilities are mainly located near the Gulf of Mexico, where many petroleum-based Plastics and synthetics produced in many states. Fiber manufacturing is mostly concentrated in the Southeast, mainly in Tennessee, Virginia, Alabama, North and South Carolina and Georgia. Plastics and resins are produced in 26 states, however, in 1992, 40% of plastic resins were produced in four states: Texas, Pennsylvania, Mississippi and Louisiana. Though California has the most facilities, Louisiana, Kentucky and Texas produce the highest value added from this sub-sector.

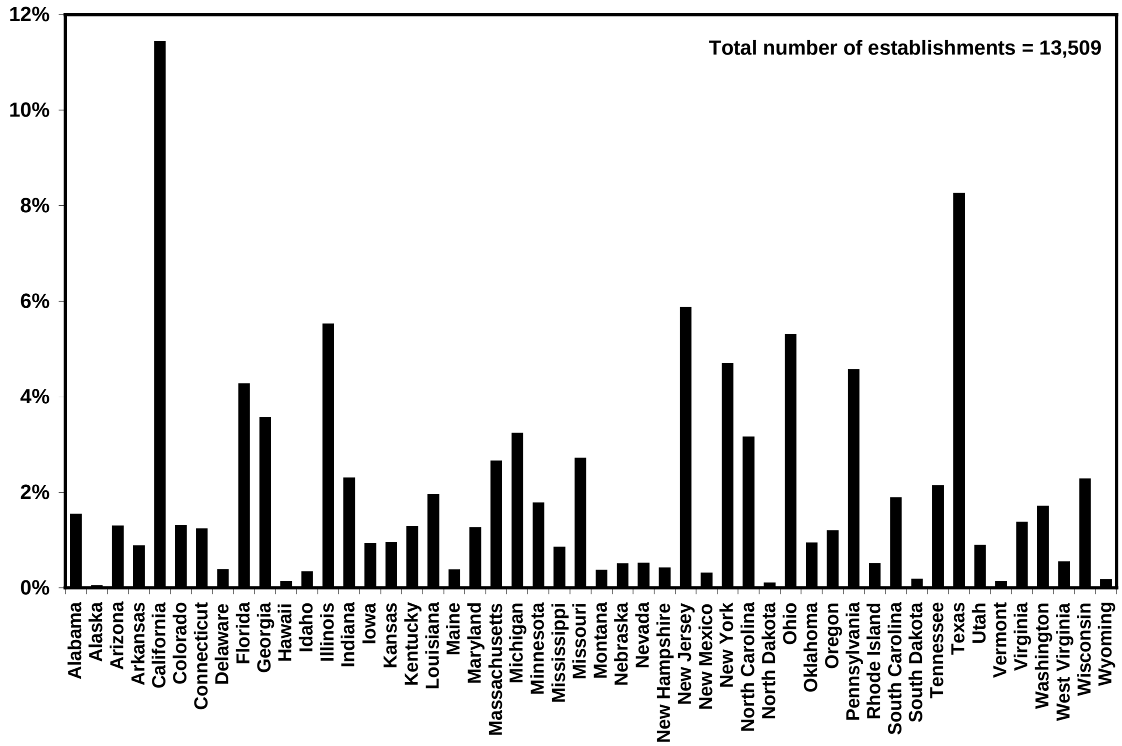

Figure 4. Number of Establishments by State in the U.S. Chemical Industry in 1997. Source: U.S. Census, Annual Survey of Manufacturers.

In the U.S., over 9,000 companies operate about 13,500 chemical plants. The inorganic chemical industry has a large number of small facilities. In 1996, 665 inorganic chemical companies operated over 1,400 facilities. The majority of these facilities employ fewer than 20 people. A few large companies produce over 25% of the pesticides and agricultural chemicals in the U.S. in the organic chemical industry, large companies of greater than 500 employees produce bulk commodities while small facilities produce specialty chemicals. Many establishments in the pharmaceuticals industry are small; almost 70% employ fewer than 50 people. Still, a relatively small number of large companies account for a large percentage of the total value of shipments and employment. In the plastics and synthetics sub-sector, facilities range in size. Most of the facilities that produce synthetic rubber are small (fewer than 20 employees), while most of the fiber manufacturing plants are large (greater than 100 employees). Although a small number of large integrated companies dominate the production of plastic resins, most of the individual establishments are small. About 71% employ fewer than 100 employees.

The inorganic chemical industry tends to grow at similar rates as overall industrial production because these products are used as intermediates in manufacturing many other products. In the late 1980, for example, the industry experienced high growth rates while in the early 1990s and 2000s, the industry saw little to no growth. The industry historically has had low profit margins, which have decreased further in recent years.

The U.S. is a major producer and exporter of agricultural chemicals. It is a net exporter of pesticide chemicals due to strong demand from developing regions of the world. It is the largest producer of phosphate-based fertilizers and pesticides and the second largest producer of nitrogen-based fertilizers in the world. Production of agricultural chemical goods is affected by changes in crops; demand is affected by planted acreage, grain prices and weather conditions. In addition, due to the large amount of exports in this sub-sector, globalization and international competition and regulatory reforms in other countries (as well as in the U.S.) will affect the demand for agricultural chemical goods in the U.S. As seen in Figure 5, after a slight increase in the early 1990s, agricultural chemical product shipments dropped back to about 1992 levels from the late 1990s to 2001.

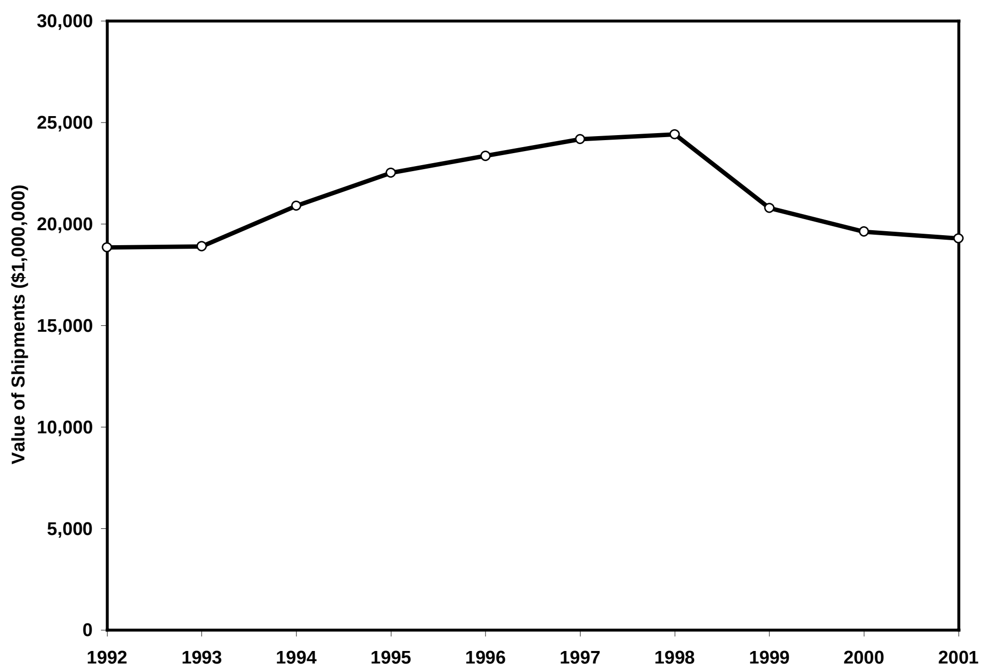

Figure 5. Value of Shipments of the U.S. Agricultural Chemicals Industry from 1992 to 2001. Source: U.S. Census, Annual Survey of Manufacturers, various years.

The U.S. has the largest organic chemicals industry in the world and is a net exporter of organic chemicals. Because many of the organic chemicals are commodities, the industry faces significant competition due to increased capacity abroad. The industry also faced decreased demand in the late 1990s due to the Asian economic crisis, worldwide overcapacity, and higher raw material and fuel costs. To combat these difficulties, the industry is consolidating rapidly. In 1999, the industry experienced approximately $45 billion worth of mergers and acquisitions. Companies are also beginning to focus on specialty chemicals in addition to commodities.

The pharmaceutical industry has seen much restructuring and many mergers in recent years, due to shorter product life cycles and cost containment pressures from managed care organizations. New products continue to enter the market, however, and the pharmaceutical industry has seen steady industry growth. Many establishments are moving abroad, however, due to the growing international market, foreign registration requirements and patent laws, and tax incentives.

The rubber and plastics industry experienced some growth early in the 1990s but that growth has leveled off in recent years. The U.S. is a major exporter of plastics. Trade with Canada and Mexico account for much of these exports; one third of the exports in 1992 were to Mexico and Canada. Worldwide overcapacity has slowed growth rates in the plastics industry. Major plastic resin manufacturers are merging and focusing on upgrading production to higher value added and specialty resins for niche markets. Fiber production facilities also are experiencing consolidation and reorganization, along with increasing their production of specialty fibers and higher value-added products. Advances in plastic resins properties are expected to increase growth and develop new end-use markets in that sub-sector. Demand for recycled and biodegradable plastics may also shape development of the industry.

2.2 The California Chemical Industry

Like the U.S., the California chemical industry produces a great variety of products. Unlike the U.S. chemical industry, however, pharmaceuticals, soaps and cleaners, and inorganic chemicals make up over 75% of shipments in the California chemical industry, with pharmaceuticals alone shipping over 50% of the products in 2000. Figure 6 shows the distribution of the value of shipments in 1997 for the eight sub-sectors of the chemicals industry in California, categorized by three-digit SIC code. Figure 7 compares the value of shipments in the California chemical industry to the U.S. chemical industry in 2000. California has much less of a focus on basic chemicals, rubbers and plastics and agricultural products than the U.S., and much more of a focus on pharmaceutical products, and other less energy-intensive high-value chemicals. Paints and soaps & cleaners are also more important in California than in the U.S. as a whole.

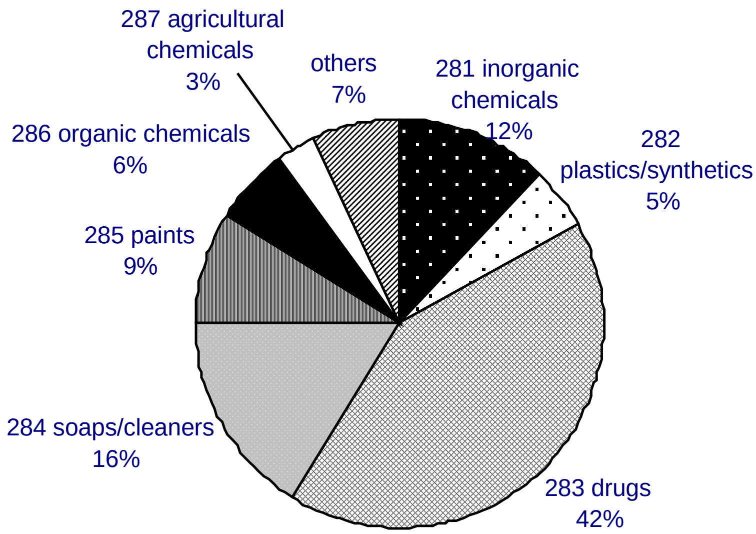

Figure 6. Value of Shipments in the California Chemical Industry in 1997 by SIC code. Source: U.S. Census, Annual Survey of Manufacturers, 1997

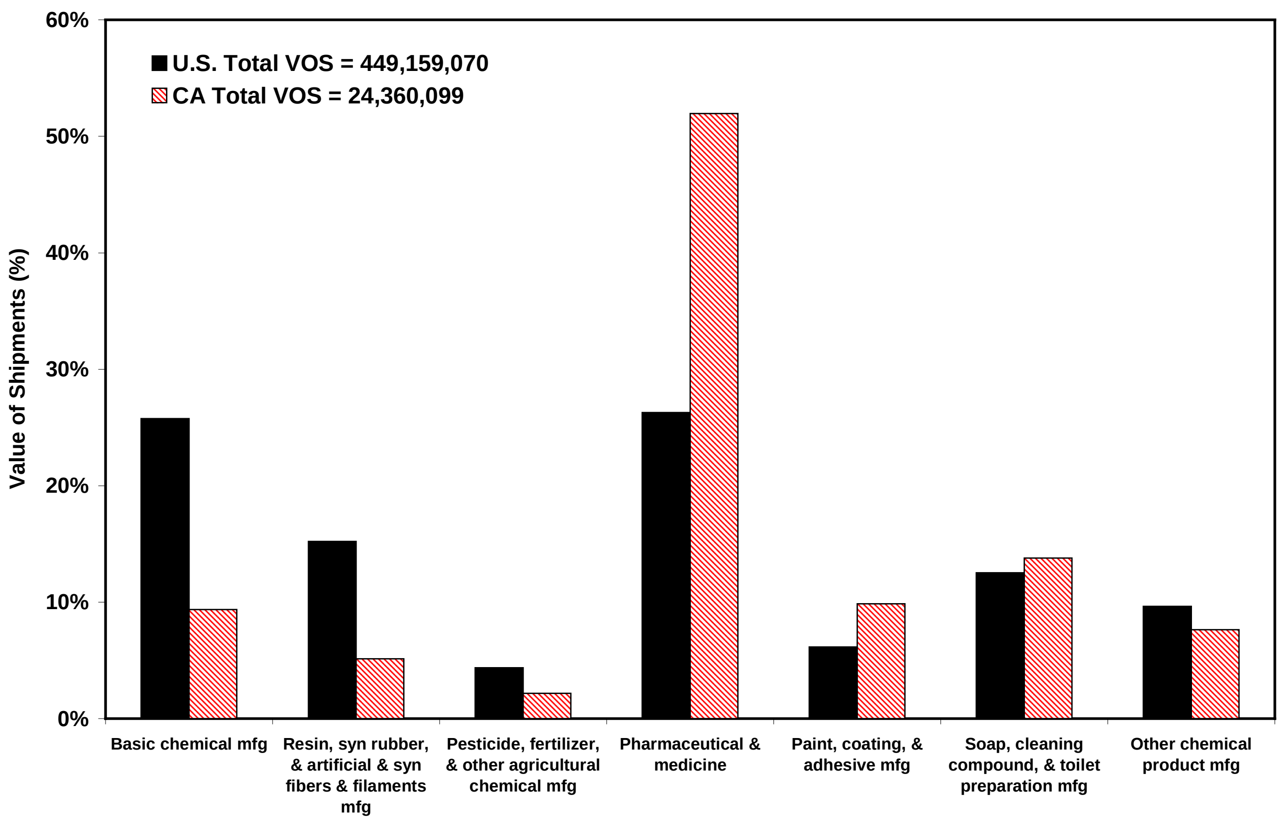

Figure 7. Value of Shipments in the California and U.S. Chemical Industries in 2000. Total value of shipments of the U.S. chemical industry is $449.2 Billion and $24.4 Billion for California. Source: U.S. Census, Annual Survey of Manufacturers, 2001

Although California ships only 5% of the chemical products in the U.S., it has the greatest number of chemical plants in the U.S. (see Figures 1 and 4). This is due to a larger number of smaller establishments and a different mix of specialty products.

In 1997, there were over 1,500 chemical plants in California. As shown in Figure 8, about 60% of those establishments are in the pharmaceuticals, paints and cleaning product sub-sectors. In 2000, these sub-sectors also made up over 75% of the value of shipments in the California chemicals industry, with pharmaceuticals alone comprising 52%. In this section, we focus on these sub-sectors. We also explore the inorganic chemicals sub-sector because of its relatively large consumption of energy (see section 3.2).

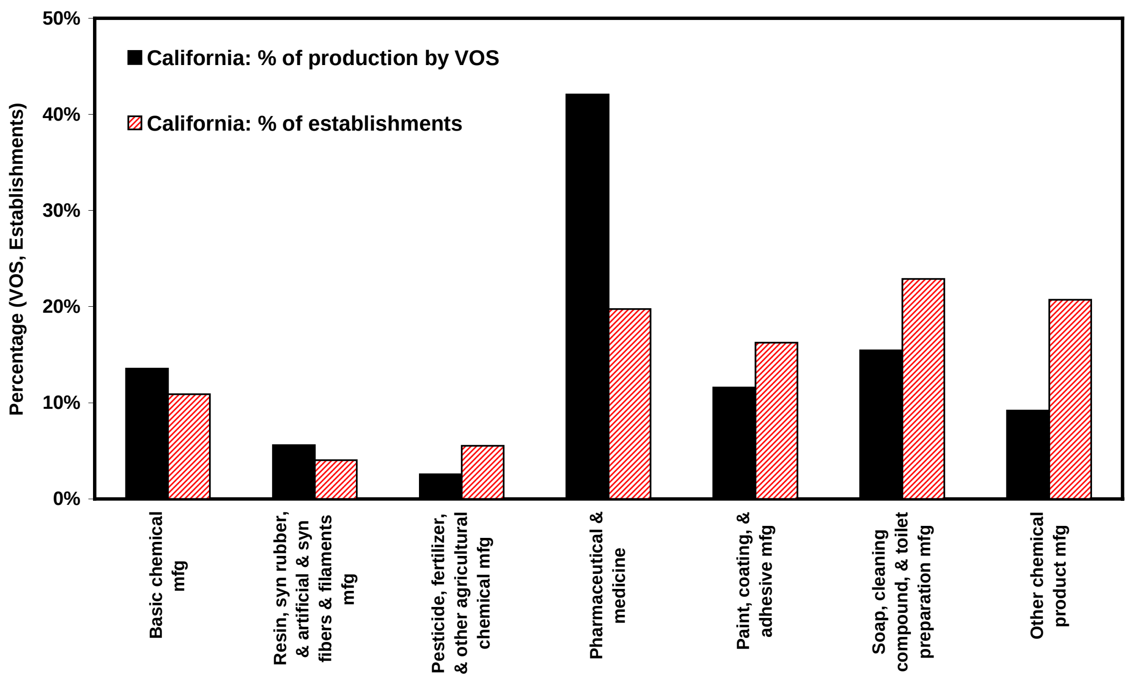

Figure 8. Distribution of the Number of Establishments and Value of Shipments in the California Chemical Industry in 1997. Source: U.S. Census, Annual Survey of Manufacturers, 1997

California's pharmaceutical sub-sector is not only the largest sub-sector in the California chemicals industry but also the sub-sector that has experienced the largest growth rate in the last few years, fueled by the discovery of new drugs and advances in the understanding of diseases. Figure 9 shows the value of shipments in this sub-sector from 1997 to 2000.

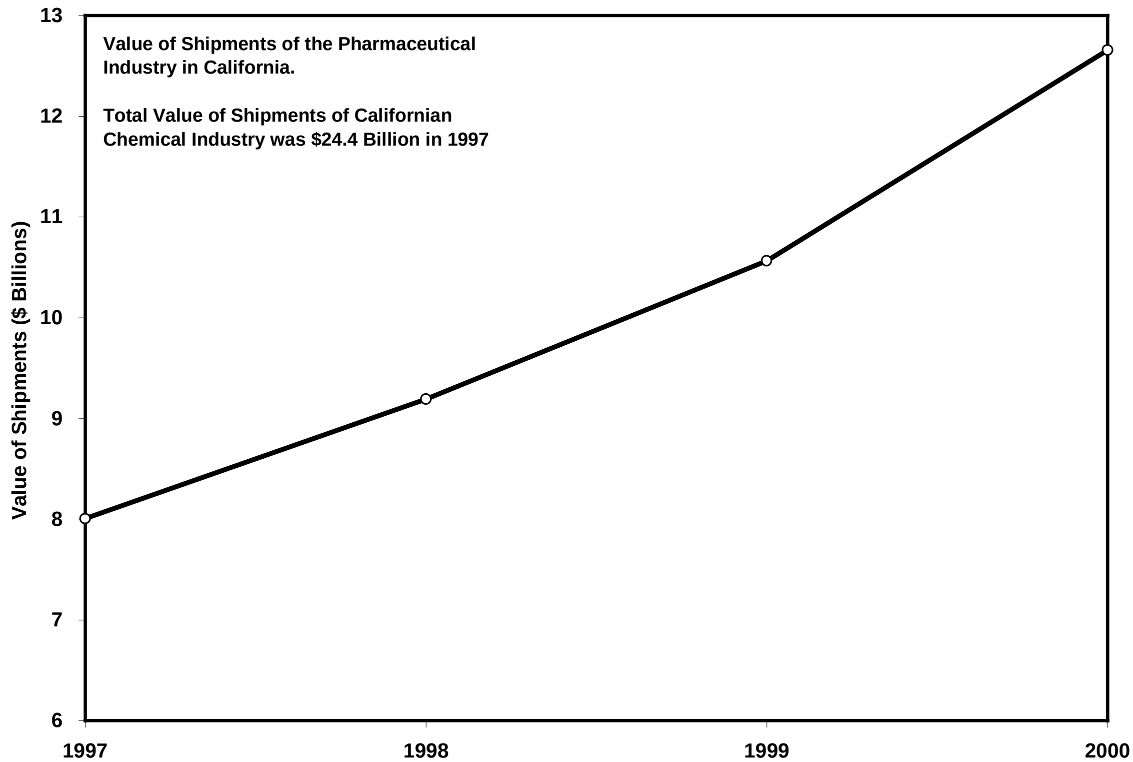

Figure 9. Value of Shipments of the California Pharmaceutical Industry from 1997 to 2000. Source: U.S. Census, Annual Survey of Manufacturers, 2000.

Pharmaceutical companies include those establishments that make pharmaceutical and medicinal products like pills, vaccines, diagnostic testing and diabetic products, as well as the producers of nutritional and herbal supplements and vitamins, food supplements and biotech products like proteins, enzymes, reagents, instruments, cell cultures and media. California has more pharmaceutical plants than any other state, but also contains some of the largest companies. The San Francisco Bay area, in particular, is home to a number of these large companies, such as Genentech, Lifescan, Alza Corp, Chiron and Bayer.

In 1997, California's soaps and cleaning products sub-sector shipped about $3 Billion, about 5% of the total paint products shipped in the U.S., ranking sixth behind Ohio (11%), New Jersey (11%), Illinois (8%), Louisiana (7%) and New York (6%). Today, soap and cleaning products make up about 14% of the value of shipments of the chemical industry in the state. The value of shipments has remained steady over the last few years, as shown in Figure 10.

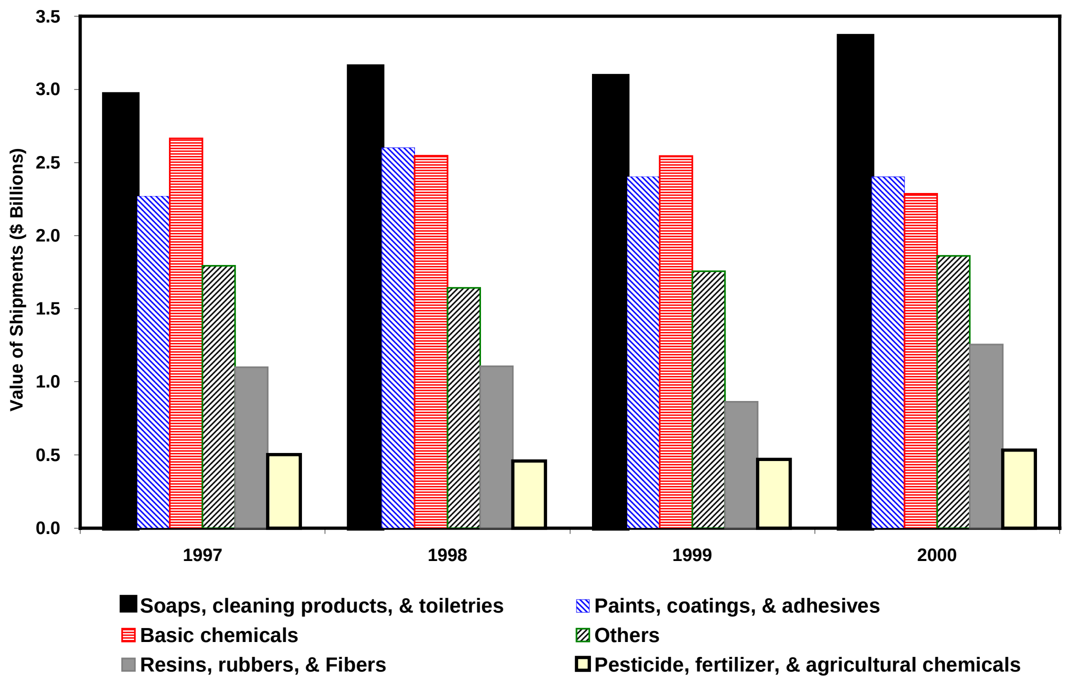

Figure 10. Value of Shipments for the industries in the chemical sector in California (excluding Pharmaceuticals, shown in Figure 9). Source: U.S. Census, Annual Survey of Manufacturers, 2000

In 1997, there were over 350 soap and cleaning product manufacturers in California, more than any other state in the U.S. The companies in this sub-sector manufacture a variety of cleaning products like soaps, detergents, softeners, shoe and lens cleaners, as well as personal care, beauty products and toiletries, air fresheners, automotive waxes and polishes. Allergan, Inc. is by far the largest producer of toiletries in California, followed by Merle Norman Cosmetics, Inc., Packaging Advantage Corp. and The Color Factory, Inc. Neutragena produces the most soaps and detergents.

In 1997, California's paint sub-sector shipped about $2,835 million, about 9% of the total paint products shipped in the U.S. Only Illinois and Ohio shipped more paint products than California. Today, paint product shipments make up about 10% of the value of shipments of the chemical industry in the state. The value of shipments has remained steady over the last few years, as shown in Figure 10.

In 1997, there were over 250 paint manufacturers in California, more than any other state in the U.S. The companies in this sub-sector manufacture a variety of coatings like ink, plastic, powder, wood furniture, concrete, polyurethane and epoxy, as well as industrial paints, indoor and outdoor paints; aerosols, dyes, laquers, clays, pigments, cement chemicals, and laminations. Kelly-Moore Paint Co., Inc. is by far the largest producer of paints in California, followed by Frazee Industries, Inc., Behr Process Corp., DUNN-Edwards Corp. and Vista Paint Corp.

The inorganic chemical industry is included as a part of the basic chemicals sub-sector, NAICS 3251, which also includes organic chemicals (although the earlier classification system, SIC, separates out the inorganic chemicals sub-sector into SIC 281). In 1997, the inorganic chemical industry made up about 12% of the value of shipments in the California chemical industry. The major categories within this sub-sector are shown in Figure 11 as a percentage of the total value of shipments in the chemical industry, both for California and the U.S. It is clear from this figure that the California industry is different from the U.S. industry. Most of the manufacturing in California consists of industrial gas production (hydrogen, nitrogen, oxygen, argon), dyes and pigments, and other basic inorganic chemical manufacturing, which includes products such as bleach, borax, sulfuric acid, plating materials, high temperature carbons & graphite products and catalysts. California produces no carbon black nor any alkalies or chlorine, which are very energy intensive processes.

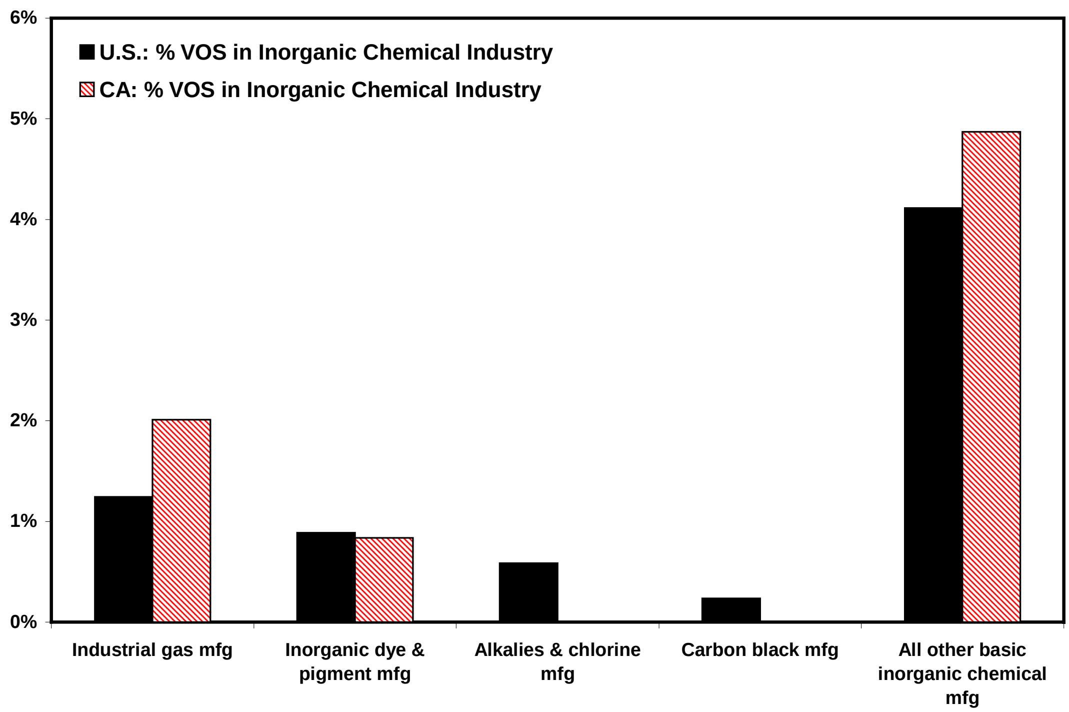

Figure 11. Distribution of the Value of Shipments in the Inorganic Chemical Industry, as a Percentage of the Total Chemical Industry for the U.S and California, excluding NAICS code 325998, all other miscellaneous chemical product and preparation manufacturing, which has some overlap with SIC code 2819, inorganic chemical manufacturing. This estimate is about 4%. Source: U.S. Census, Annual Survey of Manufacturers, 1997.

3. Energy Consumption

3.1 Energy Use of Chemical Plants in the United States

The U.S. chemical industry is the second largest consumer of energy in manufacturing (after petroleum refining). Energy use in the chemical industry varies widely as the processes and products in each of the sub-sectors vary greatly. In addition, operational factors like, maintenance practices, and age of the equipment affect energy consumption in a chemical plant from year to year.

The chemical industry as a whole is an energy intensive industry spending over $16 billion on energy purchases in 2001, $6.4 billion on electricity and $9.9 billion on fuels. Figure 12 depicts the trend in energy expenditures of the chemical manufacturing industry from 1987 to 2001. The graph shows a steady increase in total expenditures for purchased electricity and fuels, which is especially evident in the most recent years from which data is available. Energy costs as a percent of value added dropped slightly in the late 1980s and early 1990s but increased in the last few years paralleling energy costs, to its highest point in recent history. This is an important measure of energy intensity, which shows decreasing energy productivity since 1998. Figure 12 also shows a steady increase in fuel costs, due to rising natural gas prices, and a smaller but steady increase in electricity costs.

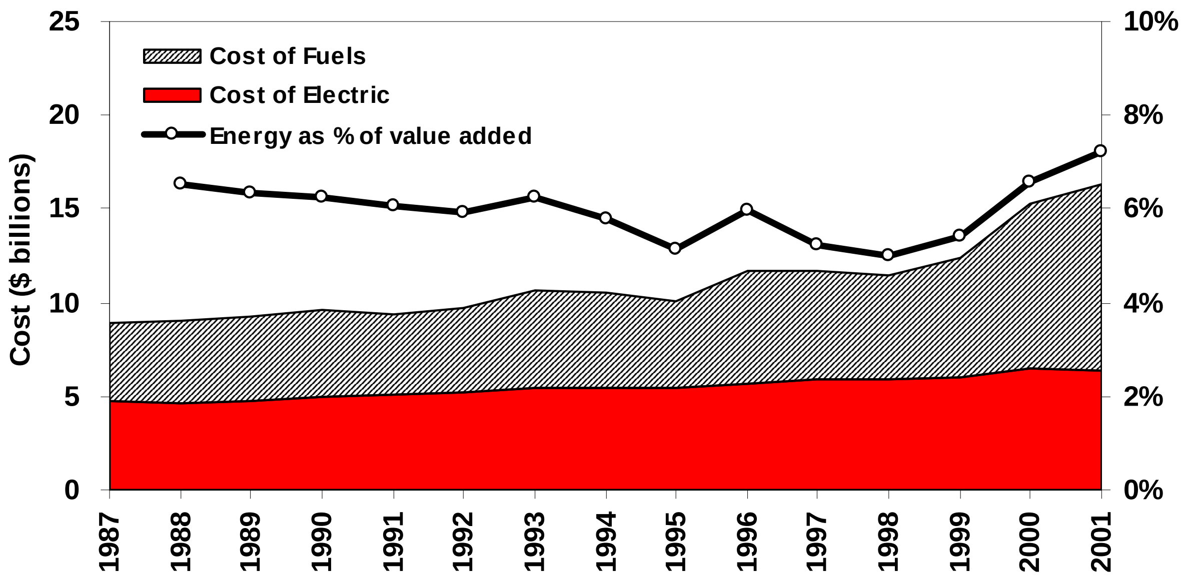

Figure 12. Annual Energy Costs of Chemical Manufacturers in the U.S. from 1987-2001. Costs are given for purchased fuels and purchased electricity. The total energy costs are given as share of the value added produced by chemical plants. Source: U.S. Census, Annual Survey of Manufacturers, various years.

In recent years, energy consumption in chemical plants has been increasing at about the same rate as production. Figure 13 shows final energy use and production since 1985 (note the scale differences). In 1998, the latest year for which data is available, total final energy consumption is estimated at 3,704 TBtu (or 3,908 PJ), representing about 21% of the final energy consumption in the U.S. manufacturing sector. Primary energy consumption[1] is estimated at 4,424 TBtu (or 4,667 PJ). The difference between primary and final electricity consumption is relatively low due to the small share of electricity consumption in the chemical plants and relatively large amount of self-produced electricity. Figure 14 illustrates energy consumption of the chemical industry by fuel for 1998. Figure 15 shows the distribution on a primary fuels basis.

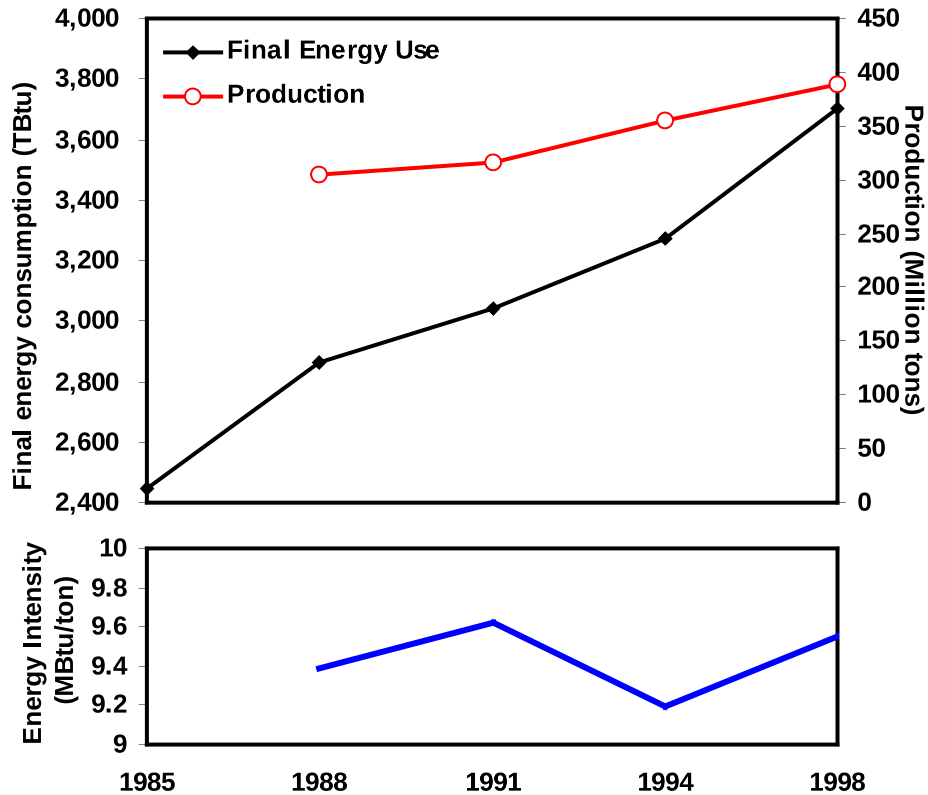

Figure 13. Annual Energy Consumption, Production and Energy Intensity (as a function of production) of Chemical Manufacturers in the U.S. from 1985-1998. Source: EIA, various years.

[1] Primary energy consumption includes the losses of offsite electricity and steam production. We assume an average efficiency of power generation on the public grid of 32%.

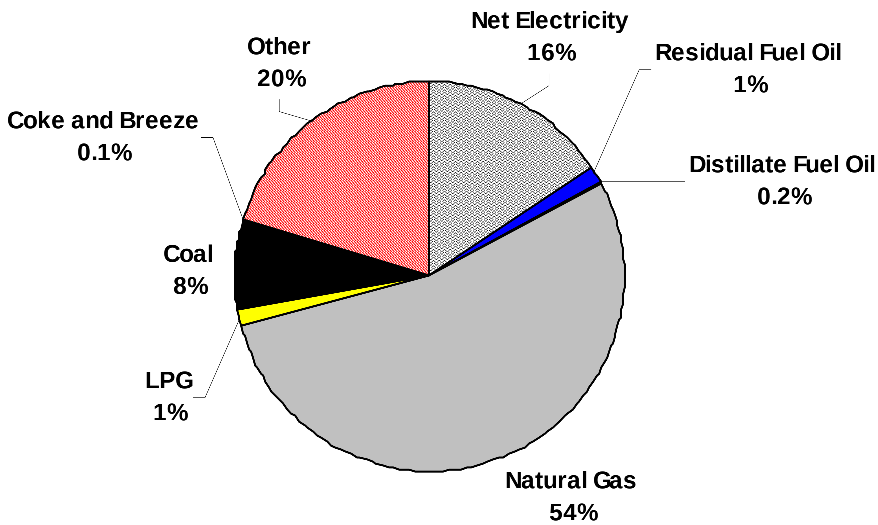

Figure 14. Final Energy Consumption of U.S. Chemical Plants in 1998.
Source: EIA, Manufacturing Energy Consumption Survey 1998.

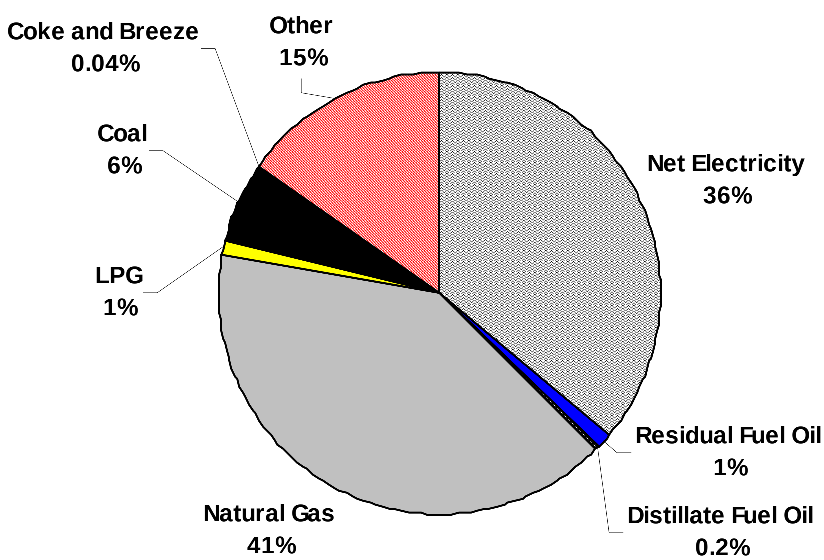

Figure 15. Primary Energy Consumption of U.S. Chemical Plants in 1998.
Source: EIA, Manufacturing Energy Consumption Survey 1998.

Figures 14 and 15 show that the main fuel used in the chemical manufacturing sector is natural gas, followed by coal. In addition to the fuels used for energy, about 2,772 TBtu of the 5,900 TBtu were used as feedstocks in 1998, or equivalent to about 47% of the total fuels consumed by the chemical industry in the U.S. Liquefied petroleum gases (LPG) account for much of the fuel used as feedstocks, about 63%, followed by natural gas, about 26%.

Electricity use has gone up in the last 15 years, tapering off in the last 5 years or so, as shown in Figure 16. Pump, fan and compressed air systems account for 66% of the electricity requirements in the U.S. chemical industry, materials processing accounts for 24%, and refrigeration for 7%.

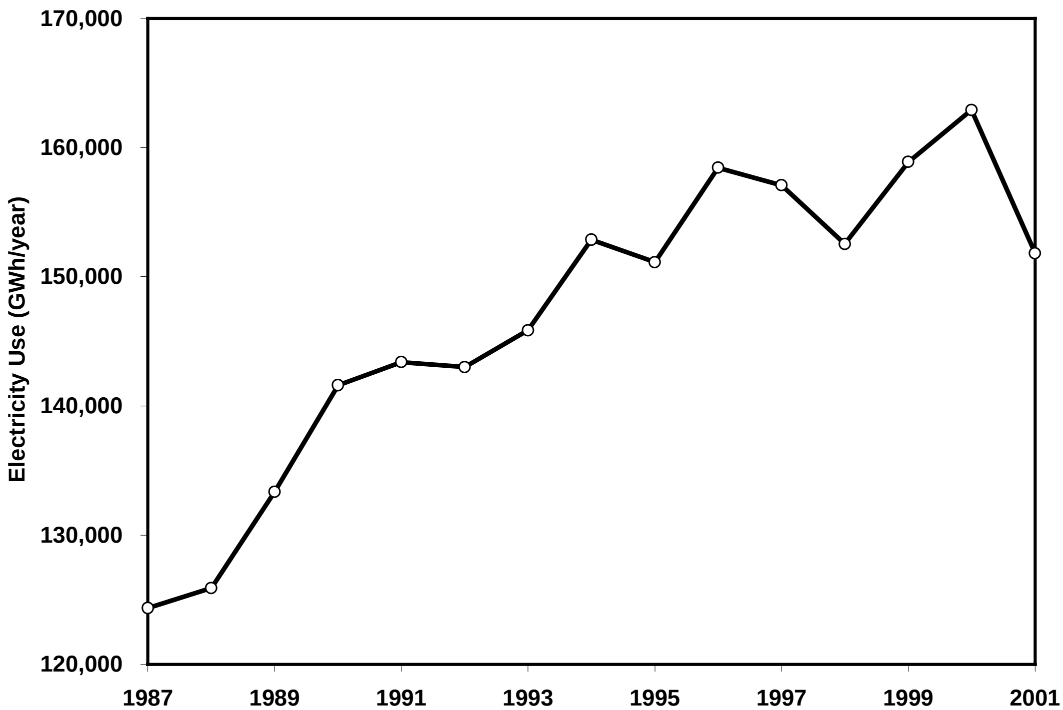

Figure 16. Electricity Consumption by the U.S. Chemical Industry from 1987-2001. Source: U.S. Census, Annual Survey of Manufacturers, various years.

The chemical industry has been an important cogenerator, generating about 20% of its electricity use in 2001. Figure 17 shows the historic development of electricity generation and purchases in chemical plants from 1987 to 2001. Cogeneration has increased slightly from about 12% to nearly 20%, with the largest increase from 1991 to 1992.

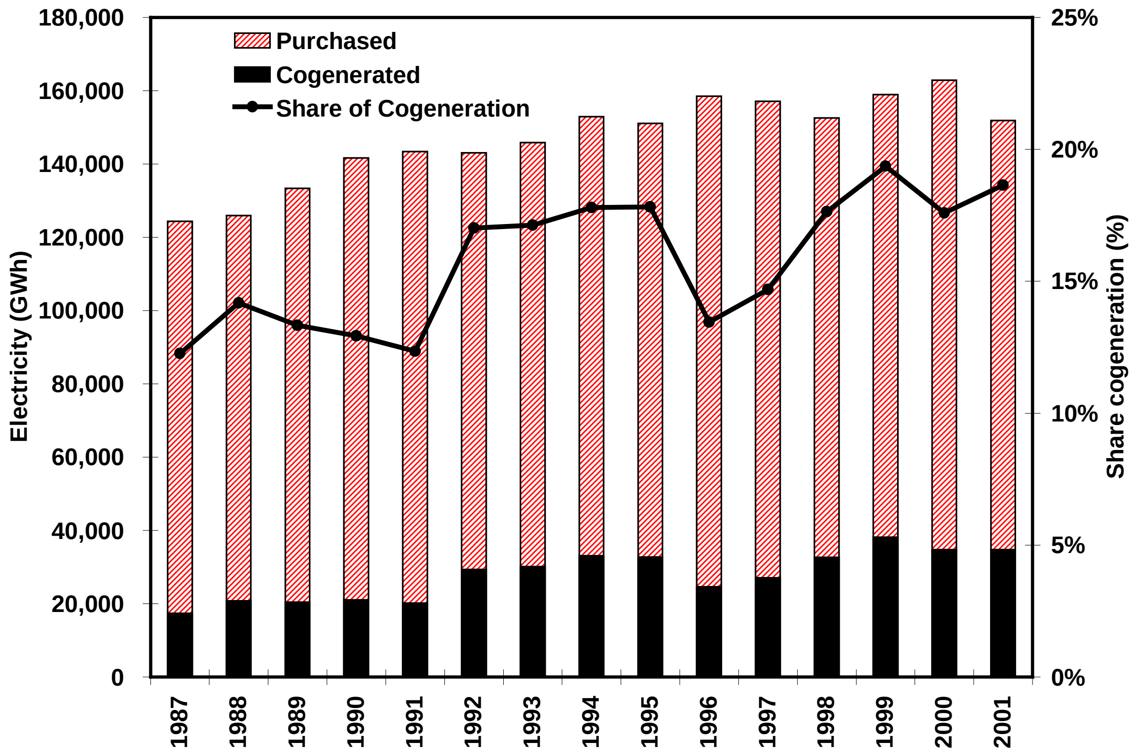

Figure 17. Electricity purchases and generation by chemical plants from 1987 till 2001. The right-hand axis expresses the share of self-generation as a function of total power consumption, excluding transfers in or electricity sold. Source: U.S. Census, Annual Survey of Manufacturers, various years.

Separations, chemical synthesis and process heating are the major energy consumers in the chemical industry. Separations account for 40 to 70% of capital and operating costs in chemical plants. Separation processes include distillation, extraction, absorption, crystallization, evaporation, drying, steam stripping, cracking, and membranes. The most widely used is distillation, accounting for up to 40% of the industry's energy use (Humphrey, 1997). Chemical synthesis consists mainly of catalytic reactions, as well as polymerization, hydration, hydrolysis and electrolysis (U.S. DOE-OIT, 1999).

Figure 18 shows the amount of energy purchased in each sub-sector of the chemical industry in the U.S., categorized by three-digit SIC code. Organic chemicals, inorganic chemicals and plastics/synthetics make up almost 80% of the energy purchases in the U.S. Figure 19 shows the distribution of electricity used in the chemicals industry. The trends are the same as overall energy use, with organic chemicals using the most electricity, followed by inorganic and plastics.

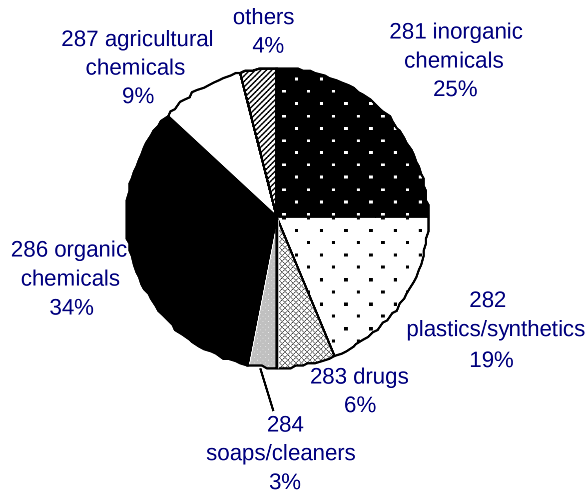

Figure 18. Energy Purchases (including feedstocks) in the U.S. Chemical Industry in 1997. Source: U.S. Census, Annual Survey of Manufacturers, 1997

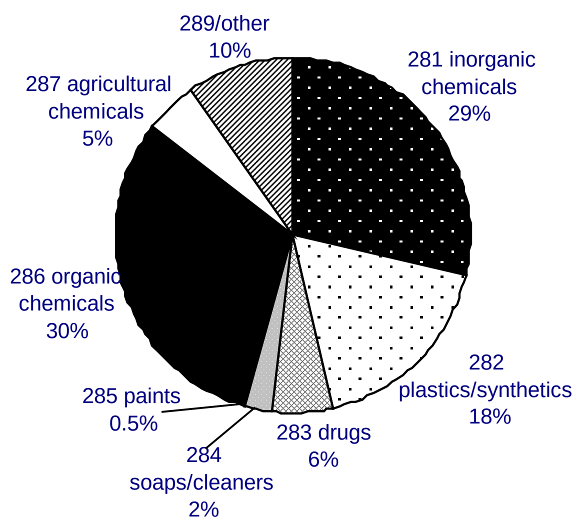

Figure 19. Electricity Distribution in the Chemicals Sector in the U.S.
Source: U.S. Census, Annual Survey of Manufacturers, 1997.

3.2 Energy Use of Chemical Plants in California

The California chemical manufacturing sector is approximately 5% of the total U.S., expressed as value of shipments, containing 11% of the number of establishments in the U.S. However, the chemical manufacturers in California feature a different, less energy intensive production structure than the U.S.-average due to differences in product mix. Hence, energy use in Californian chemical manufacturers is expected to be lower than the share of the national production (discussed in section 4.1).

There is no publicly available data on energy consumption in chemical plants in California. However, the CEC has provided data on electricity and gas use for the chemicals industry from 1990 to 2001 by SIC code. Because, as shown above in Figure 14, electricity and natural gas make up about 70% (with the remainder mainly used as feedstock) of the final energy consumed in the U.S. chemical manufacturing industry, this data should provide a good estimate of overall energy use in the industry in California. Unfortunately, though, much of the data from the CEC is categorized as "2800", or chemicals industry, not classified into sub-sectors. Figure 20 shows the electricity use by sub-sector in California for the year 2001. Clearly inorganic chemicals and pharmaceuticals are important electricity consumers in the California chemical industry. Unlike the U.S., however, the organic chemicals sub-sector is not a major electricity consumer.

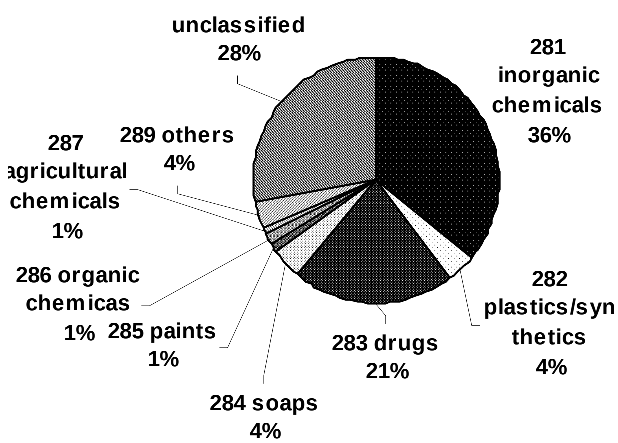

Figure 20. Electricity Use in the Chemicals industry in California divided into Sub-sectors. Source: CEC, 2003

Based on the method employed in the past (Elliott et al., 2003), we *estimated* a *theoretical* electricity distribution for the chemicals sector in California based on the value of shipments in California and U.S. trends for electricity use in the chemicals sector. That is, given a sub-sector's value of shipments in California, electricity use for that sub-sector is calculated based on the electricity that share represents on average in the U.S. Using U.S. data on electricity intensities of the chemical sub-sectors to predict electricity use for the California chemicals sector overestimates the electricity used in the organic chemicals sub-sector by approximately a factor of 16, and may underestimate the electricity used in the pharmaceuticals industry. This overestimation of the electricity use in the organic chemicals sub-sector is due, at least in part, to the fact that the plants in California do not produce energy-intensive petrochemical commodities like plants in the U.S., decreasing the electricity intensity compared to the U.S average.

Figure 21 shows the trend in electricity use over the past decade for the chemicals industry in California. Electricity use has steadily increased from 1990 to 2000, rising by 16% over the 10-year period.

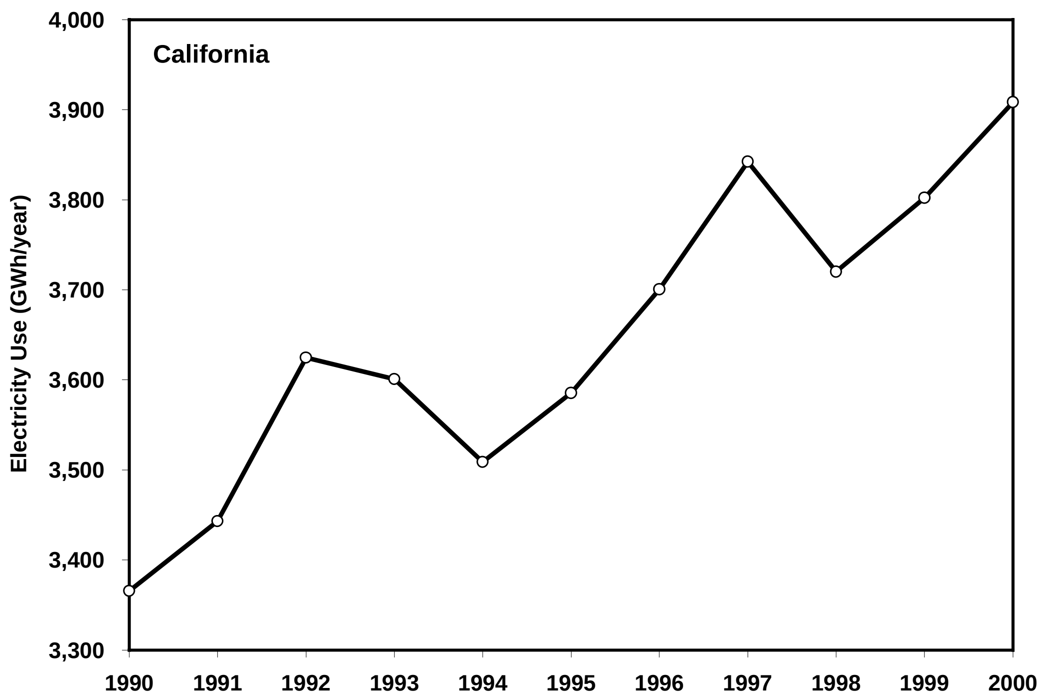

Figure 21. Electricity Consumption by the California Chemical Industry from 1990-2000.

Figure 22 shows the gas use by sub-sector in California for the year 2001. Unfortunately, most of the data is classified as chemicals, and not specified by sub-sector. Of the remaining data, the inorganic and pharmaceutical sub-sectors are the most important gas users.

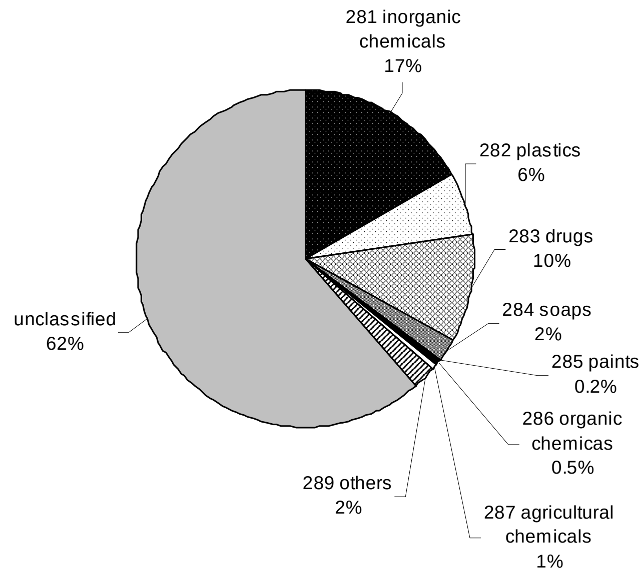

Figure 22. Natural Gas Use in the Chemicals Sector in California divided into Sub-sectors.

Figure 23 shows the trend in natural gas use over the past decade for the chemicals industry in California. Following a large drop in use in the early 1990s, natural gas use has remained flat since 1993.

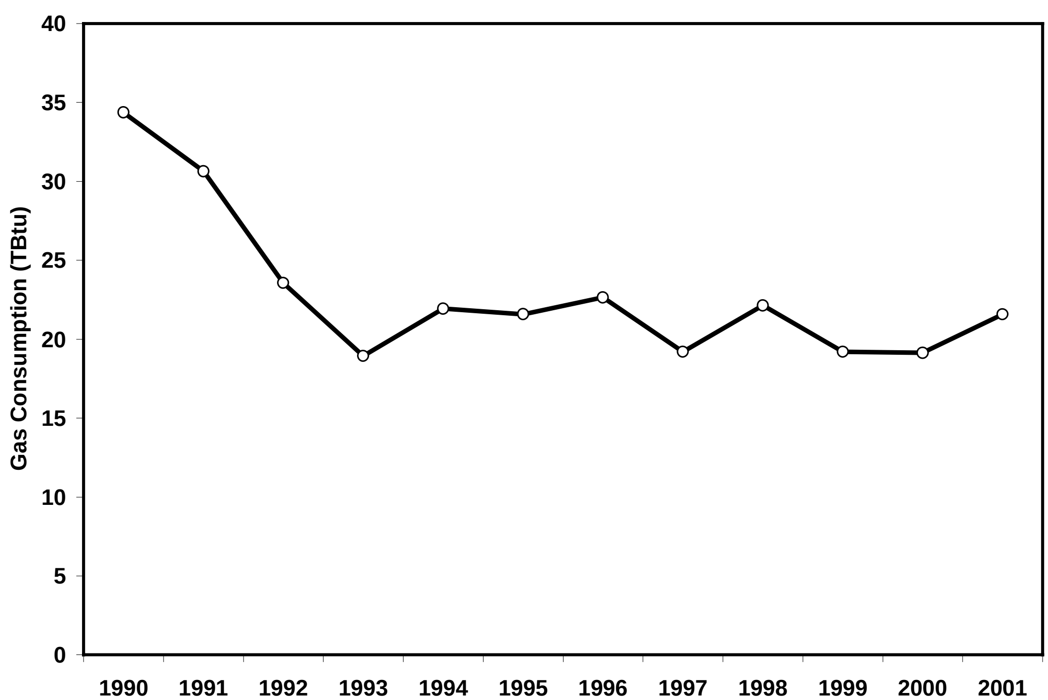

Figure 23. Natural Gas Consumption by the California Chemical Industry from 1990-2001.

Figure 24 summarizes the estimated primary energy consumption of the chemical industry in California. An uniform efficiency for power generation of 46% has been used for the whole period to estimate the primary energy consumption for power generation, following the efficiency definitions as adopted by the International Energy Agency (IEA). This is substantially higher than the national average, due to a higher penetration of more efficient natural gas based power stations and renewable energy sources in California, when compared to the rest of the country. Table 1 provides the breakdown by sub-sector (three-digit SIC).

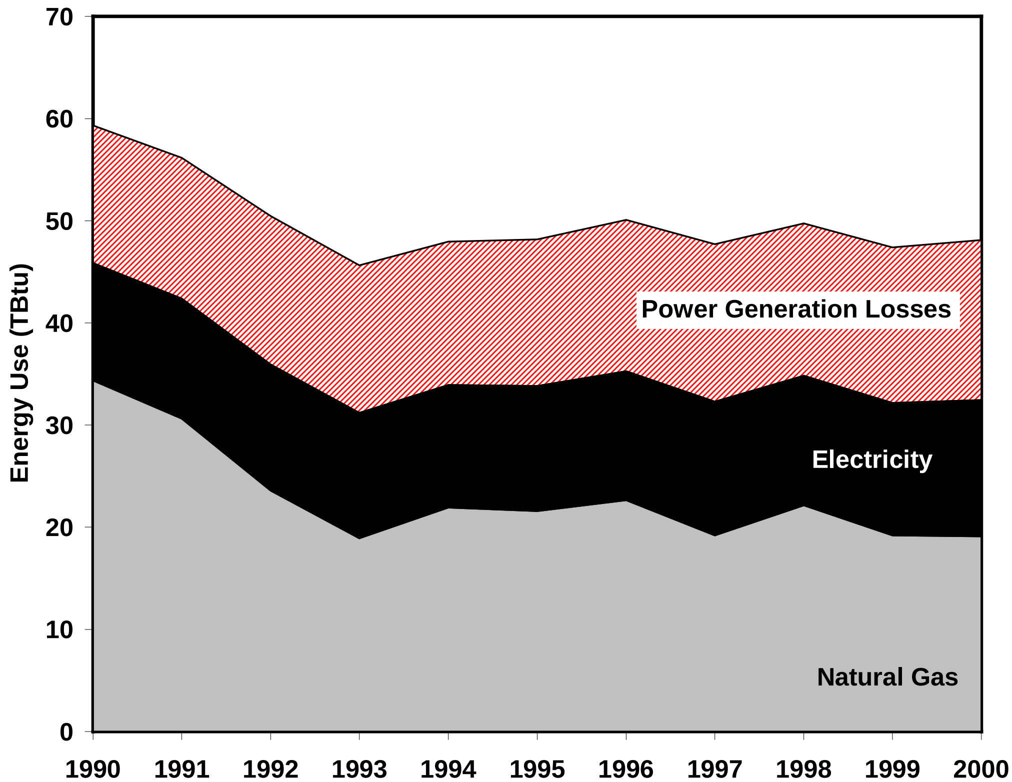

Figure 24. Primary energy consumption of the chemical industry in California. An uniform efficiency for power generation of 46% in California has been used for the whole period.

Table 1. Breakdown of energy use by three-digit SIC sub-sector in the Californian chemical industry in 2000. Electricity conversion efficiency is estimated at 46%. Between brackets the share of primary eenrgy use is given.

SIC	**Sector**	**Natural Gas (TBtu)**	**Electricity (GWh)**	**Primary Energy (TBtu)**
281	Inorganic Chemicals	5.28	1397	15.6 (32%)
282	Plastics & Synthetics	1.34	155	2.5 (5%)
283	Drugs	2.07	878	8.6 (18%)
284	Soap & Cleaners	0.43	154	1.6 (3%)
285	Paints	0.04	64	0.5 (1%)
286	Organic Chemicals	0.11	44	0.4 (1%)
287	Agricultural Chemicals	0.15	68	0.7 (1%)
289	Other	0.54	141	1.6 (3%)
	Unclassified	9.15	1008	16.6 (38%)
Total		**19.13**	**3909**	**48.13**

4. Processes in the Californian Chemical Industry

Because of the variety of chemicals produced in the many sub-sectors that make up the chemical industry in California (as described in Chapter 2), it is impossible to describe each of the manufacturing processes in detail. However, as shown in Chapter 3, the inorganic chemicals and pharmaceutical sub-sectors use more electricity than all the other sub-sectors combined. According to available data, they are also the two biggest users of natural gas nationwide. Electricity and natural gas account for over 70% of the energy used by the chemical industry. Since the manufacturers of inorganic chemicals and pharmaceuticals are clearly the biggest electricity and natural gas users in the chemicals industry in California, we will focus on these two sub-sectors. However, even within these sub-sectors, it is difficult to describe every manufacturing process that makes each drug and every inorganic chemical, and we focus on the main products and production processes in each of these sectors.

4.1 Inorganic Chemicals

In California, the main products produced in the inorganic chemicals sector are hydrogen, nitrogen, oxygen, argon, borax and bleach. (California produces no chlorine gas, an energy intensive process.) Nitrogen, oxygen and argon all involve air separation processes.

All air separation processes start with compression of air and many include compression of products to higher pressures or additional compression for products as liquid instead of gas. The cost of power is a major component of the total cost of industrial gas products. It can be two-thirds of the total cost of manufacturing. Large air separation plants consume thousands of kilowatts every hour.

Hydrogen is produced as a gas or a liquid by one of several methods. The most common and economical way to produce hydrogen is through steam reforming, a reaction of natural gas or other light hydrocarbons like ethane or propane with steam in the presence of a catalyst. Partial oxidation reacts hydrocarbons, such as natural gas, naphtha, petroleum coke or coal, with oxygen to produce hydrogen and carbon monoxide. In addition, hydrogen is obtained as a by-product of some refining and chemical production processes. Like other industrial gas manufacturing (see below), crude hydrogen is purified by pressure swing adsorption (PSA), cryogenic separation or membrane gas separation technology.

In *steam reforming***,** the natural gas feedstock reacts with steam over a catalyst, producing synthesis gas. Synthesis gas contains a mixture of carbon monoxide and hydrogen. The carbon monoxide is then reacted with steam in the water-gas-shift reaction to produce carbon dioxide and hydrogen. The carbon dioxide is removed from the main gas stream using absorption, producing hydrogen.

Energy is used in the form of fuel (to heat the reformer), steam (in the steam reforming) and power (for compression). Various licensors supply the technology. Modern variants use a physical adsorption process to remove CO_2, which uses less energy than chemical absorption processes. Most hydrogen plants are operated by a third party at or near a petroleum refinery. Most of the hydrogen is sold to the refinery, and used for conversion processes in the refinery. At least four refineries have outsourced hydrogen production: San Joaquin Refinery (Bakersfield, 3.5 million cubic feet per day (MMcfd) H_2), Shell (Wilmington, 55 MMcfd H_2), Tesoro (Golden Eagle, 31 MMcfd H_2) and Valero (Wilmington, 57 MMcfd H_2). The energy consumption for these hydrogen units is estimated at 14.5 TBtu natural gas (assuming 89% capacity utilization, based on the refinery average) and 46 MWh electricity (derived from Worrell et al., 2000).

Nitrogen is one of the largest volume industrial gases. Like hydrogen, it is also manufactured as a gas or as a liquid by one of several air separation processes. Cryogenic liquefaction and distillation accounts for approximately 85 percent of nitrogen production. It is preferred for high volume and high purity requirements. Membrane systems are used for smaller and lower purity nitrogen production because of their lower cost and simplicity. In the *cryogenic air separation* process, air is filtered, compressed and all contaminants are removed. The air is then cooled to its cryogenic temperatures through heat exchange and refrigeration processes, where it is liquefied. Often feed gases, waste gases, or product gases are used as cooling streams, whose elevated pressures are reduced, thereby chilling the streams. To maximize chilling and plant energy efficiency, the pressure reduction (or expansion) takes place inside an expander. The expander drives a compressor or electrical generator, removing energy from the gas and reducing its temperature more than would be the case with simple expansion across a valve. Because of different boiling points, the components of the partially compressed air can be separated in a distillation column. Many plants produce nitrogen, oxygen and argon all at the same plant as a part of this process. Some plants, however, product only high purity nitrogen. *Membrane separation* uses hollow-fiber polymer membranes to separate gaseous nitrogen from air by selective permeability. Oxygen diffuses more rapidly through the tube walls than nitrogen, decreasing until the product is mostly nitrogen at the desired purity level. Nitrogen emerges at elevated pressure without the need for supplemental compression. Producing nitrogen in this manner is generally less costly but produces lower purity nitrogen. *Pressure swing adsorption (PSA)* uses adsorbents in fixed beds in vessels under high pressure to remove accompanying gas impurities. Adsorbents are regenerated by countercurrent depressurization and by purging at low pressure with previously recovered near product quality gas. To obtain a continuous flow of product, a minimum of two adsorbers are used. Depending on the type of impurity to be adsorbed and removed, adsorbents are zeolitic molecular sieves, activated carbon, silica gel or activated alumina, or, most commonly, a combination of many adsorbent beds on top of one another.

Oxygen is the second-largest volume industrial gas produced, either as a gas or a liquid. When produced with nitrogen, cryogenic liquefaction and distillation are used. Based on plants built in the early 1990’s we estimate the specific energy consumption of cryogenic oxygen production at approximately 280 kWh/tonne (or 0.4 kWh/NM^3). Lower purity oxygen can be produced using vacuum pressure swing adsorption (VPSA or VSA). VSA process cycles are similar to those in PSA, but the sieve materials operate over a different pressure range. During desorption, the beds are de-pressured to vacuum conditions with the aid of vacuum pumps. The vacuum portion of VSA consumes a significant amount of power but allows the sieve material to be regenerated more fully, which increases the overall process efficiency by lowering the amount of feed air, the required feed air pressure and air compression power. Because the product delivery pressure is low, VSAs usually require an oxygen product booster or compressor. Compared to an oxygen PSA, separation power is lower, and total power, including product compression is usually lower as well. Specific power is comparable to cryogenic air separation systems.

Argon is a co-product of oxygen and nitrogen production. It is separated out during distillation. Liquid nitrogen is the first product extracted from the column, followed by a stream containing oxygen and argon (plus other gases). The crude stream contains approximately 10 percent argon. It is refined in a separate distillation column to produce argon with 98 percent purity (Praxair, 2003 http://www.praxair.com/). Manufacturers can further refine the stream by mixing the argon with hydrogen, catalytically burning the trace oxygen to water, drying and, finally, distilling the stream to remove remaining hydrogen and nitrogen. Using this process, producers can achieve an argon product with 99.9995 percent purity.

Borax is produced from raw ore that undergoes the following steps: crushing, dissolving, settling, crystallizing, filtering and drying. (The following process description is adapted from Borax, 2003, website: http://www.borax.com/practices1c.html). After the ore is crushed, the ore is mixed with a hot liquid combination of borates and water in order to dissolve the borates in water. Insoluble rocks, sand and other solids are removed using screens. Next, the saturated borate solution is pumped into large settling tanks called "thickeners." The rock and clay mixture is heavier and settles to the bottom of the tank, and the dissolved borates in water (liquor) remain on top. Liquor is cooled in tanks called “crystallizers.” In the crystallizers, the drop in temperature forces the borates to crystallize, forming a slurry of borate crystals and water. The slurry is poured over special fabric filters and washed to ensure purity. Water is removed by a vacuum filter. Damp borate crystals are then transferred to huge rotating dryers that use hot air to finish the crystal drying process.

To make **bleach**, or **sodium hypochlorite**, first chlorine must be produced, generally by breaking salt water into sodium hydroxide, hydrogen and chlorine using an electric current. This process does not take place in California where no chlorine is produced; all chlorine is shipped in by rail or truck and used as a raw material for the production of bleach. Hence, the production of bleach in California is solely a mixing process. At Clorox, for example, water and sodium hydroxide are blended together in large processing tanks (Clorox, 2003, http://www.clorox.com/science/rmp/learn.html). Then chlorine is bubbled up into this mixture through piping connected to the bottom of a tank. The pH content and strength of the solution are checked. Then the solution is filtered to remove impurities and bottled.

4.2 Pharmaceuticals

The pharmaceuticals industry spans a spectrum of activities from the research and development associated with new and innovative drugs to the mass-production of generic and over-the-counter medicines. The output product must meet stringent specifications and be produced in the shortest time possible, at minimal cost. The industry is more research intensive than most other industries, and therefore much effort takes place at a small scale. From research to mass-production, there are many products produced in the pharmaceuticals sub-sector in California, such as a variety of drugs (caplets, gels, tablets), vitamins, biochemical reagents and biotechnology products like proteins, enzymes and instrumentation. The pharmaceutical manufacturing process must maintain the highest quality and safety standards. In a batch process, the reaction stage is often the most critical, including effort to shorten the batch time to increase throughput, maintain stringent quality standards to reduce the risk of losing a batch, and reduce by-products and side reactions to improve efficiency and purity.

There are three overall stages to production of bulk pharmaceutical products – research and development, conversion of natural substances to bulk pharmaceuticals, and formulation of the final products. Figure 25 shows an overview of the main process steps in the pharmaceutical manufacturing. Each of these sections is described in more detail below.

Research & Development	**Four Stages** 1. Pre-clinical R&D: determine if substance is active and safe (6 years) 2. Clinical R&D: human testing (6 years) 3. Review of new drug application (1-2 years) 4. Post Marketing surveillance
Conversion of natural substances to bulk pharmaceutical substances	**Types of conversion:** Chemical Synthesis Fermentation Extraction
Formulation of final products	Conversion of substances at a much larger scale

Figure 25. Overview of Pharmaceutical Manufacturing.

Research & Development (R&D).
Because of being highly regulated, research and development (R&D) is the longest stage in pharmaceutical product manufacturing. After identifying several thousand compounds at the beginning stages of R&D, only one will be introduced as a new pharmaceutical drug. Many resources go into this stage of development.

The four basic stages of R&D are listed above in Figure 3; pre-clinical; clinical; review of new drug application; and post marketing surveillance. In the first pre-clinical stage, compounds are tested on animals to determine biological activity and safety. This testing takes about six years on average to complete. After pre-clinical trials, an Investigational New Drug Application (IND) is filed.

Clinical R&D is typically conducted in three phases, each with progressively more people. The first phase determines safety, the second effectiveness and the third, confirmation of safety and effectiveness along with determination of any adverse reactions. Stage two altogether takes about six years on average to complete. At this point, the pharmaceutical company files a New Drug Application (NDA). As of 1996, approval times for the NDA are approximately 15 months. Finally, various ways of formulating the drug on a larger scale will be evaluated for optimum delivery.

Conversion to bulk pharmaceutical substances.
Bulk pharmaceutical substances are produced via fermentation, extraction, chemical synthesis or a combination of these processes (EPA, 1997). Most steroids, antibiotics, and some food additives, like vitamins, are produced by fermentation. Enzymes and digestive aids, allergy relief medicines, hematological agents, insulin, anti-cancer drugs and vaccines are extracted from naturally occurring substances. Antihistamines, cardiovascular agents, central nervous system stimulants and hormones are produced by chemical synthesis. Antibiotics, antineoplastic agents, central nervous system depressants and vitamins are produced by more than one of these processes.

Most substances are produced using chemical synthesis in batch processes. Bulk pharmaceutical products are manufactured differently; some with several intermediates and various purification methods. In this section, we discuss the major steps involved in the manufacturing of bulk pharmaceuticals, although some manufacturing processes do not include each step while some produce intermediates require several iterations of the same step.

Chemical Synthesis.
Figure 26 shows a simplified diagram of the chemical synthesis manufacturing process for pharmaceuticals. Each one of these stages is described below.

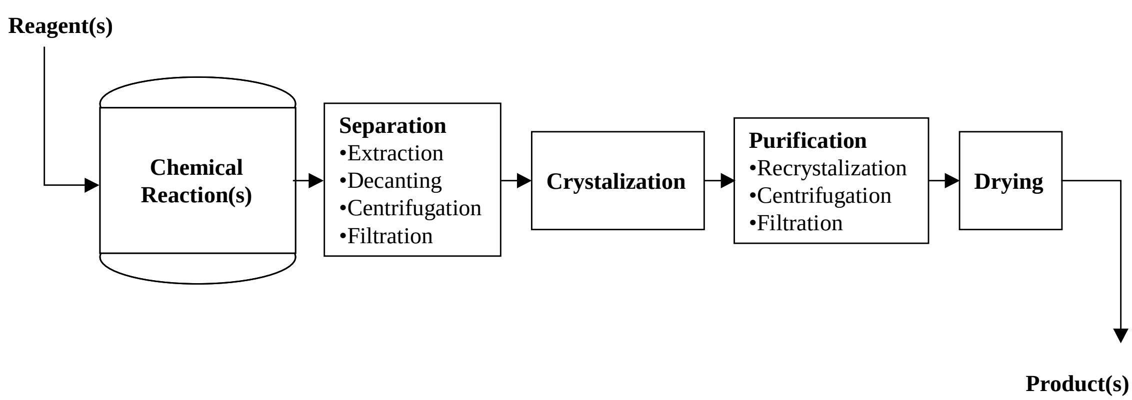

Figure 26. Simplified Chemical Synthesis Diagram (Adapted from EPA, 1997.)

Reaction. Raw materials are fed into the reactor vessel, where reactions such as alkylations, hydrogenations or brominations are performed. The most common type of vessel is the kettle-type reactor. These reactors, generally stainless steel or glass-lined carbon steel, range from 50 to several thousand gallons capacity. The reactors may be heated or cooled, and reactions may be performed at atmospheric pressure, elevated pressure or in a vacuum. Generally, both reaction temperature and pressure are monitored and controlled. Nitrogen may be required for purging the reactor, and some intermediates may be recycled back to the feed. Some reactions are mixed with an agitator of some sort. In addition, a condenser system may be required to control vent losses.
Reactors are often attached to pollution control devices to remove volatile organics or other compounds from vented gases.

Separation. The main types of separations are extraction, decanting, centrifugation, filtration and crystallization. Crystallization is used by many plants and is discussed separately, below.

Extraction is used to separate liquid mixtures. Extraction takes advantage of the differences in the solubility of the mixture components. A solvent that preferentially combines with only one of the components is added to the mixture. The extract containing the combined liquid can be easily separated from the other, the raffinate or residual phase.

Decanting is a simple method that removes the liquids from insoluble solids that have settled to the bottom of a reactor or settling vessel. The liquid over the solid is either pumped out of the vessel or poured from the vessel leaving the solid and a small amount of liquid.

Centrifugation removes solids from a liquid stream using the principle of centrifugal force. By rotating the centrifuge, an outward force pushes the liquid through a filter that retains the solid phase. The solids are manually scraped off the sides of the vessel or with an internal scraper. To avoid air infiltration, centrifuges are usually operated under nitrogen and kept sealed during operation.

Filtration separates fluid/solid mixtures by flowing fluid through a porous media while retaining most of the solid particulates. Batch filtration systems widely used by the pharmaceutical industry are plate and frame filters, cartridge filters, nutsche filters and combination filters/dryers.

Crystallization. Crystallization is a widely used separation technique and is often used alone or in combination with one or more of the techniques above. Crystallization separates solutes that have crystallized out of solution from the rest of the mixture. A supersaturated solution is formed by cooling the solution, evaporating a portion of the solvent or adding a third component. The solute that has crystallized is removed from the solvent by centrifugation or filtration.

Purification. Purification follows separation, and typically uses the separation methods described above. Several steps are often required to achieve desired purity. Recrystallization is a common technique for purification. Washing with additional solvents and filtration is also sometimes used.

Drying. The final step in chemical synthesis is drying the product (or intermediates). Drying is done by evaporating the solvents from the solids. Solvents may then be condensed for reuse or disposal. The pharmaceutical industry uses several different types of dryers including tray dryers, rotary dryers, drum or tumble dryers or pressure filter dryers. Prior to 1980, the most common type of dryer used by the pharmaceutical industry was the vacuum tray dryer. Today, however, the most common dryers are tumble dryers or combination filter/dryers. In the combination filter/dryer, the slurry is first filtered into a cake, after which, a hot gaseous medium is blown up through the filter cake until the desired level of dryness is achieved. Tumble dryers range in capacity from 20 to 100 gallons. A rotating conical shell enhances solvent evaporation while blending the contents of the dryer. Tumble dryers utilize hot air circulation or a vacuum combined with conduction from heated surfaces.

Product Extraction.

Pharmaceuticals that are extracted from natural sources are often present in very low concentrations. The volume of finished product is often an order of magnitude smaller than the raw materials, making this an inherently expensive process.

Precipitation, purification and solvent extraction methods are used to recover active ingredients in extraction. Solubility can be changed by pH adjustment, salt formation or the addition of an anti-solvent to isolate desired components in precipitation. Solvents can be used to remove active ingredients from solid components like plant or animal tissues, or to remove fats and oils from the desired product. Ammonia is often used in natural extraction as a means of controlling pH.

Fermentation.

In fermentation, microorganisms are typically inoculated in a liquid at particular temperature, pH, aerobic or anaerobic conditions that are conductive to rapid growth, producing the desired pharmaceutical as a by-product of normal metabolism. The process involves three main steps: inoculum and seed preparation, fermentation and product recovery.

Seed preparation. The fermentation process begins with seed preparation, where inoculum is produced at laboratory scale. Typically, 1 to 10% of the production tank volume is created in this stage to be used in the production fermentor (EPA, 1997).

Fermentation. After creating the inoculum at laboratory scale, the media is charged to the fermentor. Generally, the fermentor is agitated, aerated and controlled for pH, temperature and dissolved oxygen levels. The fermentation process lasts from hours to weeks, depending on the product and process.

Product Recovery. When fermentation is complete, the product needs to be recovered from the filtered solids. Solvent extraction, direct precipitation and ion exchange may be used to recover the product. If the product is contained within the microorganism used in fermentation, heating or ultrasound may be required to break the cell wall. Organic solvents are used in one method of product recovery to separate the product from the aqueous solution. The product can then be removed from the solvent by crystallization. Some products can be directly precipitated out of solution using precipitating agents like metal salts. In ion exchange, the product adsorbs onto an ion exchange resin. Solvents, acids or bases are used to recover the product from the resin.

Formulation of Final Products.
The final stage of pharmaceutical manufacturing is converting manufactured bulk substances into final, usable forms. Common forms of pharmaceutical products include tablets, capsules, liquids, creams and ointments, aerosols, patches and injectable dosages. Tablets account for the majority of pharmaceutical solids taken orally in the U.S.

To prepare a tablet, the active ingredient is combined with a filler, such as sugar or starch, a binder, such as corn syrup or starch, and sometimes a lubricant, such as magnesium state or polyethylene glycol. The filler ensures the proper concentration, and the binder bonds tablet particles together and a lubricant may facilitate equipment operation during the manufacturing of the tablets or slow disintegration of the active ingredients. Tablets are produced by compression of powders. Wet granulation or dry granulation may be used. In wet granulation, the active ingredient is powdered and mixed with the filler, wet, blended with the binder in solution, mixed with lubricants and finally compressed into tablets. Dry granulation is used when tablet ingredients are sensitive to moisture or drying temperatures. In dry granulation, larger tablets are made initially which are then ground, screened and recompressed into final tablet sizes. Coatings, if used, are done in a rotary drum in which the coating solution is poured onto the rotating tablets. Once coated, they are dried in the drum and may be polished.

Capsules are the second most common solid oral pharmaceutical product (after tablets). Capsules are constructed using a mold to form the shell, while ingredients are then poured (hard capsules) or injected (soft capsules) into the mold. Temperature controls the viscosity of the gelatin, which determines the thickness of the capsule walls.

Active ingredients for liquids formulations are first weighed then dissolved in their liquid. The solutions are mixed in glass-lined or stainless steel vessels and tanks. Preservatives may be added to prevent mold and bacterial growth. If the liquid is to be used orally or for injection, sterilization is required.

Ointments are made by blending its active ingredient with a petroleum derivative or wax base. The mixture is cooled, rolled out, poured into tubes and packaged. Creams are semisolid emulsions of oil in water or water in oil, which are heated separately and then mixed together.

Table 2 shows the estimated energy use for the pharmaceutical industry as a whole, categorized by end use and by activity area. These estimates do not refer to any particular plant, nor do they attempt to estimate the energy use at a "typical" pharmaceutical plant[2]. In addition, Table 2 shows the main energy uses for each activity area and end use category. This list may not apply to all facilities nor is it assumed to be exhaustive.

Table 2. Estimation of overall energy use in the pharmaceutical industry and major energy users in each building or activity area.

	Overall	**Plug loads and processes**	**Lighting**	**Heating, ventilation and air conditioning (HVAC)**
Total	100%	20%	15%	65%
R&D	35%	Microscopes Centrifuges Electric mixers, Analysis equipment Sterilization processes Incubators Walk in/Reach in areas (refrigeration)	Task and overhead lighting	Ventilation for clean rooms and fume hoods Areas requiring 100% makeup air Chilled water Hot water and steam
Offices	10%	Office equipment including computers, fax machines, photocopiers, printers Water heating (9%)*	Task, overhead and outdoor lighting	Space heating (25%)* Cooling (9%)* Ventilation (5%)*
Bulk Manufacturing	30%	Centrifuges Sterilization processes Incubators Dryers Separation processes	Task and overhead lighting	Ventilation for clean rooms and fume hoods Areas requiring 100% makeup air Chilled water Hot water and steam
Formulation, Packaging & Filling	15%	Mixers Motors	Mostly overhead, some task	Particle control ventilation
Warehouses	5%	Forklifts Water heating (5%)*	Mostly overhead lighting	Space heating (41%)* Refrigeration (4%)*
Miscellaneous	5%		Overhead	

* Percentages derived from Commercial Building Energy Consumption Survey (CBECS) data for commercial office or warehouse buildings. These numbers are only shown as first approximations and in reality will vary from facility to facility.

The main energy using processes in the pharmaceutical industry are HVAC, including the clean room and equipment to maintain the production environment needs for pharmaceutical production, including heating, cooling, ventilation, air conditioning and air dehumidification. Clean room energy use in the pharmaceutical industry is estimated at 660 GWh (Tschudi et al., 2002), representing a very large part of the total electricity use in the pharmaceutical industry. This includes electricity use for cooling and heating

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[2] Because of the variability between plants in the industry today, including some facilities which only contain one activity area listed in Table 3, we do not attempt to define a "typical pharmaceutical plant".

the airflow into the clean rooms. Tschudi et al. (2001) provide a breakdown for energy use in a typical clean room, showing that the main energy uses are fans (30%), HVAC pumps (20%), chillers (14%) and nitrogen production (12%).

5. Energy Efficiency Opportunities and Technology Development

5.1 Introduction

The previous sections have shown that the Californian chemical industry is distinctly different from that of the nation's average. It also shows that a wide variety of processes are used and products made. In this section, we will not evaluate the design of the next generation chemical plants. We will discuss some important technology development directions for chemical industries, with an emphasis on the challenges faced by the Californian chemical industries. We focus on the main development areas and the discussion, almost by definition, is not exhaustive. The discussion below is guidance for the SIOF roadmap process, and does not intend to prescribe any selection or menu of technologies. This section aims to help the roadmap-process for technology development needs for the California Industries of the Future and other R&D programs by providing input to the process by the industry and California Energy Commission and other participants.

The chemical industry and the U.S. Department of Energy have developed a number of R&D roadmaps for the chemical industry. Roadmaps have been developed for biocatalysis, combinatorial chemistry, computational chemistry, computational fluid dynamics (CFD), materials of construction, materials technology, new process chemistry, reaction engineering, and separations. Materials for future roadmaps have been developed for nanomaterials, alternative media, catalysis and process measurement and control. Reports on these areas can be downloaded from the website of the Office of Industrial Technologies of the U.S. Department of Energy (http://www.oit.doe.gov/chemicals/). Information on specific areas can be found on the website of the Council for Chemical Research (http://www.ccrhq.org/vision/index.html).

5.2 Process Control & Management

Energy management comprises a large variety of measures such as recognizing the importance of energy management, planning, monitoring, and implementing optimal control strategies. Generally, no or low initial costs are involved with these measures. We focus on process monitoring and energy management technologies. It is stressed that training and motivation are important, if not essential, measures in energy management, and should be an integral part of industrial energy management, as well as introduction of new technologies. A variety of process control systems are available for virtually any industrial process. A wide body of literature is available assessing control systems in most industrial sectors such as chemicals and petroleum refining. Table 3 provides an overview of classes of process control systems.

Table 3. Classification of Control Systems and Typical Energy Efficiency Improvement Potentials.

System	Characteristics	Typical energy savings (%)
Monitoring and Targeting	Dedicated systems for various industries, well established in various countries and sectors	Typical savings 4-17%, average 8% , based on experiences in the UK
Computer Integrated Manufacturing (CIM)	Improvement of overall economics of process, e.g. stocks, productivity and energy	> 2%
Process control	Moisture, oxygen and temperature control, air flow control "Knowledge based, fuzzy logic"	Typically 2-18% savings

Note: The estimated savings are valid for specific applications (e.g. lighting energy use). The energy savings cannot be added, due to overlap of the systems. Sources: (Caffal 1995, Martin et al., 2000).

Many modern energy-efficient technologies depend heavily on precise control of process variables. Applications of process control systems are growing rapidly, and modern process control systems exist for virtually any industrial process. Still, large potentials exist to implement control systems, and more modern systems enter the market continuously. Modern control systems are often not solely designed for energy efficiency, but rather at improving productivity, product quality and efficiency of a production line. Applications of advanced control and energy management systems are in varying development stages and can be found in all industrial sectors. Control systems result in reduced downtime, reduced maintenance costs, reduced processing time, and increased resource and energy efficiency, as well as improved emissions control (CADDET 1997). Downtime reduction is especially important when using batch processes. Special control technologies have been developed to schedule and optimize the use of batch processes in the pharmaceutical industry. Various vendors have developed technology just for this purpose, and are applied by many pharmaceutical companies. For example, Genentech has purchased technology developed by Agilisys to control one of its production facilities.

Process control systems depend on information of many stages of the processes. A separate but related and important area is the development of sensors that are inexpensive to install, reliable, and analyze in real-time. Development aims at the use of optical, ultrasonic, acoustic, and microwave systems, that should be resistant to aggressive environments (e.g. oxidizing environments in furnace or chemicals in chemical processes) and withstand high temperatures. The information of the sensors is used in control systems to adapt the process conditions, based on mathematical ("rule"-based) or neural networks and "fuzzy logic" models of the industrial process. *Neural network-based control systems* have successfully been used many process industries. New energy management systems that use artificial intelligence, fuzzy logic (neural network), or rule-based systems mimic the "best" controller, using monitoring data and learning from previous experiences. *Process knowledge based systems* (KBS) have been used in design and diagnostics, but are hardly used in industrial processes. KBS incorporates scientific and process information applying a reasoning process and rules in the management strategy.

Although, energy management systems are already widely disseminated in various industrial sectors, the performance of the systems can still be improved, reducing costs and increasing energy savings further. For example, total site energy monitoring and management systems can increase the exchange of energy streams between plants on one site. Traditionally, only one plant or a limited number of energy streams were monitored and managed. Various suppliers provide site-utility control systems.

Research for advanced sensors and controls is ongoing in all sectors, both funded with public funds and private research. Several projects within DOE's Industries of the Future program try to develop more advanced control technologies (US DOE-OIT, 2000). Sensors and control techniques are identified as key technologies in various development areas including energy efficiency, mild processing technology, environmental performance and inspection and containment boundary integrity. Sensors and controls are also represented in a crosscutting OIT-program. Outside the U.S., Japan and Europe also give much attention to advanced controls. Future steps include further development of new sensors and control systems, demonstration in commercial scale, and dissemination of the benefits of control systems in a wide variety of industrial applications.

5.3 Process Optimization and Integration

Process integration or pinch technology refers to the exploitation of potential synergies that are inherent in any system that consists of multiple components working together. In plants that have multiple heating and cooling demands, the use of process integration techniques may significantly improve efficiencies.

Developed in the early 1970's it is now an established methodology for continuous processes (Linnhoff, 1992; Caddet, 1993). The methodology involves the linking of hot and cold streams in a process in a thermodynamic optimal way (i.e. not over the so-called 'pinch'). Process integration is the art of ensuring that the components are well suited and matched in terms of size, function and capability. Pinch analysis takes a systematic approach to identifying and correcting the performance limiting constraint (or pinch) in any manufacturing process (Kumana, 2000a). It was developed originally in the late 1970's at the University of Manchester in England and other places (Linnhoff, 1993) in response to the "energy crisis" of the 1970's and the need to reduce steam and fuel consumption in oil refineries and chemical plants by optimizing the design of heat exchanger networks. Since then, the pinch approach has been extended to resource conservation in general, whether the resource is capital, time, labor, electrical power, water or a specific chemical species such as hydrogen.

The critical innovation in applying pinch analysis was the development of "composite curves" for heating and cooling, which represent the overall thermal energy demand and availability profiles for the process as a whole. When these two curves are drawn on a temperature-enthalpy graph, they reveal the location of the process pinch (the point of closest temperature approach), and the minimum thermodynamic heating and cooling requirements. These are called the energy targets. The methodology involves first identifying the targets and then following a systematic procedure for designing heat exchanger networks to achieve these targets. The optimum approach temperature at the pinch is determined by balancing the capital-energy tradeoffs to achieve the desired payback. The procedure applies equally well to new designs as well as retrofit of existing plants.

The analytical approach to this analysis has been well documented in the literature (Kumana, 2000b; Smith, 1995; Shenoy, 1994). Energy savings potential using Pinch Analysis far exceeds that from well-known conventional analysis techniques such as heat recovery from boiler flue gas, insulation and steam trap management.

Pinch analysis and competing process integration tools have been developed further in the past years. The most important developments in the energy area are the inclusion of alternative heat recovery processes such as heat pumps and heat transformers, as well as the development of pinch analysis for batch processes (or in other words, bringing in time as a factor in the analysis of heat integration). Furthermore, pinch analysis should be used in the design of new processes and plants, as process integration goes beyond optimization of heat exchanger networks (Hallale, 2001). Even in new designs, often additional opportunities for energy-efficiency improvement can be identified. The pinch analysis has also been extended to the areas of water recovery and efficiency, and hydrogen recovery (Hydrogen Pinch, see also below). Water used to be seen as a low-cost resource to the refinery, and was used inefficiently. However, as the standards and costs for wastewater treatment increase and the costs for feedwater makeup increase, the industry has become more aware of water costs. In addition, large amounts of energy are used to process and move water through the refinery. Hence, water savings will lead to additional energy savings. Water Pinch can be used to develop targets for minimal water use by reusing water in an efficient manner. Optimization software has been developed to optimize investment and operation costs for water systems in a plant (Hallale, 2001). New tools have been developed to optimize water and energy use in an integrated manner (Wu, 2000). Water Pinch has until now mainly been used in the food industry, reporting reductions in water intake of up to 50% (Polley and Polley, 2000). We did not identify any Water Pinch analysis case studies specific for the chemical industry.

The key area of importance for the chemical industry in California is the integration and optimization of batch processes. While the methodology for application of pinch analysis to batch processes is not new (Kemp and Deakin, 1989, Obeng and Ashton, 1988), the market has not caught on, and is nowhere close to reaching its full potential. Two R&D projects carried out under the auspices of the Best Practice program in the UK on batch process integration identified an energy savings of 8 percent and 40 percent respectively. In the first case, in a resin factory, a key savings was the use of condenser heat to pre-heat the reactor fuel and material feeds. These case studies demonstrate that energy savings are not necessarily limited to energy intensive industries, but could have significant applicability to food, pharmaceutical, fine chemicals and other industries where batch processes dominate (ETSU, 1999). The major benefit here is not necessarily energy, but productivity of capital and labor. The resource being conserved is processing time, through better scheduling and proper matching of equipment functionality, which means one can get more output from the same plant, or save capital when building a new plant for a given production rate. The thermal integration of the processes is closely connected to optimal scheduling of the batch processes to improve productivity and maintain product quality. This provides an important area for R&D.

5.4 Energy Recovery

Hydrogen production was identified as one of the large energy users in the chemical industry in California. Hydrogen, produced in dedicated hydrogen plants, is often sold and used in the petroleum refinery in processes such as hydrocrackers and desulfurization using hydrotreaters. These processes and other processes generate gases that may contain a certain amount of hydrogen not used in the processes, or generated as by-product of distillation of conversion processes. In addition, different processes have varying quality (purity) demands for the hydrogen feed. Reducing the need for hydrogen make-up will reduce energy use in the reformer and reduce the need for purchased natural gas. Natural gas is an expensive energy input in the refinery process, and lately associated with large fluctuation in prices (especially in California). The major technology developments in the hydrogen management within the refinery are hydrogen process integration (or hydrogen cascading) and hydrogen recovery technology. Revamping and retrofitting existing hydrogen networks can increase hydrogen capacity between 3% and 30% (Ratan and Vales, 2002). For a more in-depth discussion of hydrogen recovery technologies see the SIOF report on refineries (Worrell and Galitsky, 2004).

Hydrogen integration is a new and important application of pinch analysis (see above). Most hydrogen systems feature limited integration and pure hydrogen flows are sent from the reformers to the different processes in the neighboring refinery. But as the use of hydrogen is increasing, especially in Californian refineries, the value of hydrogen is more and more appreciated. Using the approach of composition curves used in pinch analysis the production and uses of hydrogen of a refinery can be made visible. This allows identification of the best matches between different hydrogen sources and uses based on quality of the hydrogen streams. It allows the user to select the appropriate and most cost-effective technology for hydrogen purification (Hallale, 2001). The analysis method accounts also for costs of piping, besides the costs for generation, fuel use and compression power needs. It can be used for new and retrofit studies. Although this will result in reduced hydrogen production needs in the chemical industry the main opportunities are found in the petroleum refinery, and not in the hydrogen plant itself.

Hydrogen recovery is an important technology development area to improve the efficiency of hydrogen recovery, reduce the costs of hydrogen recovery and increase the purity of the resulting hydrogen flow. Hydrogen can be recovered indirectly by routing low-purity hydrogen streams to the hydrogen plant or can be recovered from offgases by routing it to the existing purifier of the hydrogen plant or by installing additional purifiers to treat the offgases and ventgases. Membranes are an attractive technology for hydrogen recovery. If the content of recoverable products is higher than 2-5% (or preferably 10%), recovery may make economically sense. Various suppliers offer membrane technologies for hydrogen recovery, including Air Liquide, Air Products and UOP.

5.5 Catalysts

Catalysts are key to the conversion and processing efficiency of all conversion processes in the chemical industry. Many scientific groups around the world are active in catalyst research and development, while a number (26 in 2001) of major catalyst suppliers operate worldwide to supply and recycle catalysts. Finding new catalysts is much like a trial-and-error process, although recent progress in the combinatorial development programs have led to accelerated development rates of new catalysts. Nevertheless, many new interesting developments in catalysts for the chemical industry are underway. Due to the wide variety of processes used in the chemical industry in California, it is impossible to select an area within catalyst development with a potential major impact on energy use. The major energy using processes in California using catalysts are hydrogen production and plastic and resin manufacture, while specialized catalysts may be used in the pharmaceutical industry. As part of the Chemicals IOF program, roadmaps for catalysis have been developed.

In catalyst development the emphasis is on new ways to accelerate the development of new catalysts, and to improve the selectivity of catalysts to 100%, as well as development of catalysts that work at lower temperatures (reducing energy use). Of special interest to the fine chemicals industries in California, is the area of biocatalysis, for which the identified priority areas are the identification of the contents of a biocatalyst developmental toolbox, and the development of mediators and electrodes for electrically coupling enzymes (including photochemical). There is also the need for tools for computational biology to develop better descriptions of enzyme mechanisms, and to find ways to improve understanding of metabolic pathway engineering and develop better tools for probing metabolism of whole cells (Scouten and Petersen, 2000).

5.6 Reactor Design

While new processes are developed by many of the suppliers to the oil industry, most of these represent slight changes to previous designs, improving productivity, energy efficiency and lowering production costs. However, from a R&D perspective there are also important new approaches to reactor design. Below we will discuss some of the interesting new developments in process and reactor design in the petroleum refining industry. Important in optimal reactor design is also basic knowledge on reaction chemistry, as well as development of technologies like computational fluid dynamics (CFD).

One of the most promising pathways to simultaneously reduce energy use and capital costs is *process intensification*. Process intensification is a new area of reactor development aiming at more compact reactors to dramatically reduce the size of chemical plants, reduce capital costs and intensify the chemical reactions (Stankiewicz and Moulijn, 2000). Process intensification started in the early 1990's and was taken up by the British energy agency as potential approach to improve energy efficiency. Process intensification aims at the design of new compact reactors, and on the combination and integration of different processes (e.g. conversion and separation). The former has given rise to the development of compact heat exchangers that work under more extreme conditions (see e.g. Haslego, 2001). An example of the latter is the design by Sulzer and a European consortium to integrate the chemical conversion with a distillation column (Moritz and Gorak, 2002).

The major new development area for conversion processes will be the combination of conversion and separation, i.e. *reactive distillation*. By combining the chemical reaction and separation in one reactor, capital costs are reduced and energy efficiency is improved through better integration of these process steps. Reactive distillation offers a promising alternative to conventional reaction-distillation schemes (Sundmacher and Kienle, 2003). Furthermore, active removal of reaction products can help shift the equilibrium of the reaction and improve the conversion efficiency. Reactive distillation has mainly been used in acetate technology (e.g. MTBE production) (Moritz and Gorak, 2002). Various research institutes and technology developers aim at developing new applications of reactive distillation. In Europe, a collaborative project of suppliers and universities aims to improve understanding of reactive distillation and develop simulation tools to design new applications. Other new developments include the use of monolithic structures that contain the catalysts (Babbich and Moulijn, 2003), reducing catalyst loss (Goetze and Bailer, 1999). Monolithic structures result in low-pressure drop.

Membranes may offer future alternatives to distillation and other separations. Membranes have started to enter the chemical industry. Membrane technology should be evaluated as an integrated part of the specific process for which it’s being implemented to warrant the full energy savings potential.

5.7 Biotechnology

Biotechnology is one of the main drivers for the high-value products of the Californian chemical industry. Although, the total energy consumption of the pharmaceutical industry in California is limited, it contributes to about 50% of the value of shipments, making it an important area. Important areas within the biotechnology area are bio-catalysis (see section 5.5), bio-separation (see section 5.8) as well as a better understanding and development of methods to accelerate the development of new biotechnological processes (including microbes) and improve the efficiency (currently often low yields at long processing times and low density), controllability, and specificity of the conversion processes. While some of the issues particular for biotechnology development have been addressed in IOF roadmaps on alternative reaction engineering (Klipstein and Robinson, 2001) and alternative media (Breen, 1999), there is no single place where the main R&D needs and directions in biotechnology development, relevant for the Californian chemical industry, have been discussed.

5.8 Separations

Separation processes are important energy users, and warrant special attention in the development of a roadmap for energy-efficiency improvement in the chemical industry. The most common separation processes are distillation, crystallization, adsorption, extraction, and membranes. New areas focus on reactors that combine reaction and distillation (e.g. reactive distillation, see above), ion exchange and bio-separation, as well as the development of hybrid processes. An extensive roadmap has been prepared by the American Institute of Chemical Engineers and U.S. Department of Energy (Adler et al., 2000).

Given the unique structure of the chemical industry in California, a focus on gas separations, as well as separations used in the pharmaceutical industry (e.g. crystallization, extraction and bioseparations), as well as water removal, is warranted.

5.9 Combustion Technology

Combustion is key in many of the processes used in hydrogen production and other processes in the organic and inorganic chemical industries. Boilers, furnaces and process heaters all apply burners to efficiently generate heat to produce steam, electricity and heat. Burner development is challenged by many issues. Foremost are challenges to reduce emissions from burners (i.e. NOx, CO, PM), as well as to increase the heat transfer and combustion efficiency of the burner. Other challenges include fuel flexibility, robust operating controls, improved safety, reliability and maintenance and lower costs (US DOE-OIT, 2002b). Small changes in the efficiency of combustion systems may provide large energy cost savings. Also, the use of low-NOx burners may result in indirect capital and energy savings, as it avoids the use of selective catalytic reduction. Hence, combustion technology is still an important R&D area with potential for new technologies.

U.S. DOE has produced a roadmap for the combustion industry outlining the major challenges and R&D directions for burners in boilers and furnaces (US DOE-OIT, 2002b). New burner designs aim at improved mixing of fuel and air and more efficient heat transfer. Many different concepts are developed to achieve these goals, including lean-premix burners (Seebold et al., 2001), swirl burners (Cheng, 1999), pulsating burners and rotary burners (U.S. DOE-OIT, 2002c). It is impossible to outline all potential burner developments in this report, and hence we refer to roadmap.

5.10 Clean Rooms

As discussed in Chapter 3 and 4, clean rooms, include conditioning of the incoming and exiting air, are responsible for a major part of the energy consumption in the pharmaceutical industry. Lawrence Berkeley National Laboratory and the California Energy Commission have developed a technology roadmap for clean room design. The roadmap aims at a 50% reduction in specific energy consumption, while maintaining or improving productivity and safety. Challenges are found in the current regulations and measurement of clean room performance, and the need for improved design and operation tools (Tschudi et al., 2002). Integration and optimal design of the different elements of a clean room will likely result in substantial energy savings. Design groups in e.g. California, Ireland and Finland look at different designs and applications.

The new Genentech facility in Vacaville (California) has adopted several incremental improvements in clean room design and was able to achieve annual energy savings of over $500,000 at an attractive payback.

5.11 Utilities

As a large part of energy use in the pharmaceutical and other chemical industries is used in motors and other utilities, it becomes an important area for energy efficiency improvement. New technology development in pumping (e.g. dry vacuum pumps), power technology (e.g. adjustable speed drives and power electronics) and compressors can result in direct energy savings. The relative high power costs in California make these new technologies attractive. Also, new wastewater treatment technology may help reduce the effluent quantity and improve the quality. New technologies like reverse osmosis (RO) and other membrane technology may soon enter the refinery as well. RO has been used widely in the food industries to upgrade feedwater and also treat wastewater.

5.12 Power Generation

The chemical industry is a large user of cogeneration or Combined Heat and Power production (CHP). The chemical industry is also identified as one of the industries with the largest potential for increased application of CHP (Onsite, 1997).

Where process heat, steam or cooling and electricity are used, cogeneration plants are significantly more efficient than standard power plants because they take advantage of what are losses in standard plants by utilizing waste heat. In addition, transportation losses are minimized when CHP systems are located at or near the refinery. Utility companies have been developing CHP for use by refineries. In this scenario, the utility company owns and operates the system for the refinery, which avoids the capital expenditures associated with CHP projects, but gains the benefits of a more energy efficient system of heat and electricity. For systems requiring cooling, absorption cooling can be combined with CHP to use waste heat to produce cooling power.

Innovative gas turbine technologies can make CHP more attractive for sites with large variations in heat demand. *Steam injected gas turbines* (STIG, or Cheng cycle) can absorb excess steam, e.g. due to seasonal reduced heating needs, to boost power production by injecting the steam in the turbine. The size of typical STIGs starts around 5 MWe. STIGs are found in various industries and applications, especially in Japan and Europe, as well as in the U.S. Energy savings and payback period will depend on the local circumstances (e.g. energy patterns, power sales conditions).

6. Summary and Conclusions

The chemical industry is an important part of the Californian economy. The Californian chemical industry includes a very wide mix of products, with the dominant sub-sectors being pharmaceuticals, inorganic chemicals, organic chemicals, plastics and resins and soap and detergents. The structure of the Californian chemical industry varies widely from that of the United States. In California the focus is on industries with a relatively low energy-intensity (with a few exceptions) producing high value chemicals from intermediates feedstocks produced elsewhere. This sets the Californian chemical industry apart from the nations industry, warranting special attention in an Industries of the Future program.

We estimate the primary energy consumption of the chemical industry in California at 48 TBtu in 2000 (51 PJ), excluding hydrocarbon feedstocks from petroleum products. The most important energy users in the Californian chemical industry are inorganic chemicals (e.g. industrial gases, borax) and pharmaceuticals. Data on energy use as reported by the utilities has severe limitations, as over a third of the energy use in the chemical industry is not classified properly.

Due to the large differences between the Californian and U.S. chemical industries the areas for energy-efficiency improvement also vary. Table 4 summarizes the major areas for energy R&D in the chemicals industry in California.

T*able 3. Major technology development directions for the petroleum refining industry.*

Technology Area	**Technology Examples**
Process Control	Neural networks, knowledge based systems, improved sensors
Process Optimization and Integration	Analytical tools, site integration, batch process integration
Energy Recovery	Hydrogen recovery and integration (with petroleum refining)
Catalysts	Higher selectivity, increased lifetime, bio-catalysts
Reactor Design	Process intensification, reactive distillation
Biotechnology	Improved controllability, selectivity and efficiency
Separations	Membranes, crystallization
Combustion Technology	Low NOx burners, high-efficiency burners
Clean rooms	New integrated and efficient designs
Utilities	Membranes, low-maintenance pumps
Power Generation	Advanced cogeneration

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